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Abstract

The existing empirical literature on Taylor-type interest rate rules has failed to achieve a robust consensus. Indeed, the relatively common finding that the Taylor principle does not hold has fueled a degree of controversy in the field. We attribute these mixed estimation results to a raft of empirical issues from which many existing studies suffer, including bias, inconsistency, endogeneity and a failure to adequately account for the combination of persistent and stationary variables. We propose a new method of combining $I(0)$ and $I(1)$ series in a system setting based on the long-run structural approach of Garratt, Lee, Pesaran and Shin (2006). The application of this method to a long sample of US data provides modest support for the operation of a Taylor-type rule, albeit with considerable inertia. We argue that estimation across rolling windows may better reflect shifts in the underlying preferences of the monetary policymakers at the Federal Reserve. Such rolling estimation provides substantial evidence that the inflation and output preferences of the Fed have varied through time, presumably reflecting the prevailing economic and political conditions, its chairmanship, and the composition of the Federal Open Market Committee. Our most significant finding is that the Taylor Principle was robustly upheld under Volcker, often upheld pre-Volcker but rarely observed post-Volcker over any horizon.

JEL Classifications: C13, C51, E58, N10.

Key Words: System Estimation with Mixed $I(0)$ and $I(1)$ Variables, Long-Run Structural Modelling, Rolling Estimation, Taylor Rule.

*Address for correspondence: M. Greenwood-Nimmo, G19 Maurice Keyworth Building, University of Leeds, Moorland Road, Leeds (UK), LS2 9JT. Email: mjgn@lubs.leeds.ac.uk. All computational routines are available on request. We are grateful to Yongsung Chang, Seunghoon Cho, Till Van Treeck and seminar participants at Yonsei University and the IMK (Düsseldorf) for their many helpful comments. The second author acknowledges partial financial support from the ESRC (Grant No. RES-000-22-3161). The usual disclaimer applies.

1 Introduction

Existing empirical research into Taylor-type interest rate rules has failed to achieve anything but a weak consensus regarding their properties. Motivated in part by the empirical difficulties faced by standard empirical Taylor rules, ranging from pervasive residual serial correlation to a failure to observe the Taylor principle[1], a large literature has developed around various modifications of Taylor's original specification. Among the most common modifications are the addition of dynamic terms (surveyed by Sack and Wieland, 2000), the development of forward-looking models (*e.g.* Clarida, Galí and Gertler, 2000), the use of real time data (*e.g.* Orphanides, 2000) and the augmentation of Taylor's covariates with additional series such as asset prices and exchange rate indices (*e.g.* Siklos, Werner and Bohl, 2004).

Carare and Tchaidze (2005) argue that the lack of consensus in this expansive literature results from the failure of existing empirical techniques to distinguish between the competing models. Focusing simply on the standard static and dynamic models, we attribute the mixed empirical findings to two principle factors. Firstly, we demonstrate that many existing studies suffer from a raft of model mis-specification issues. For example, OLS estimation of the single-equation static model is generally inefficient in the presence of residual autocorrelation and is inconsistent if the true unobserved data generating process is inertial (Judd and Rudebusch, 1998). Furthermore, both single-equation static and dynamic models may suffer from contemporaneous endogeneity of the regressors, which is likely to be a particularly serious issue in the case of inflation due to its persistence. Finally, we observe that the failure to adequately account for the possibility of cointegration among Taylor's variables may result in spurious regression (Österholm, 2005)). The second factor that we aim to identify is the importance of multiple observed and unobserved preference-shifts in the objective function of the Federal Reserve in recent decades. These may be substantial shifts in the policy stance such as the move away from quantity-based monetary policy, or more subtle shifts, relating to the relative weight attached to different economic indicators in each meeting of the Federal Open Market Committee, for example.

We contribute to this literature by deriving a simple system model capable of coherently combining the persistent and stationary series of interest. This represents the first serious attempt at bridging the $I(0)$ vs. $I(1)$ gap in a system setting and extending the spirit of the single-equation bounds-testing approach of Pesaran, Shin and Smith (2001) to this more complex case. We argue that this strategy should provide more reliable estimation results than the common single-equation models as it explicitly corrects a number of the shortcomings of the latter. Furthermore, as a system model it will provide a firm basis for rich dynamic analysis incorporating a variety of feedback effects that are explicitly omitted from single-equation models. Moreover, based on the long-run structural modelling framework advanced by Pesaran and Shin (2002), we demonstrate that structural inferences can be drawn from our model using Sims' orthogonalisation technique owing to the stationarity of the output gap. One of the principle advantages of our model is its ability to evaluate both the nominal and real interest rate response to a shock in a dynamic fashion and to illuminate the underlying causal relationships among the three variables in the system. This leads us to argue that the traditional static interpretation of the Taylor principle is inadequate and that it is best addressed in a dynamic framework such as ours that takes full account of the time path not just of the nominal interest rate but also of inflation (and thereby the real interest rate) following an initial shock.

[1]The Taylor principle states that if monetary policy is to act in a stabilising manner, it must ensure the procyclicality of the real interest rate. That is to say that when inflation increases by $a\%$, the central bank must raise the short-term nominal interest rate by $b > a\%$, thereby raising the real rate by approximately $(b - a)\,\%$. Failure to adhere to this simple rule is thought to result in destabilising (explosive) monetary policy which actively propagates and amplifies disequilibria.

Our estimation results over the period 1964q2 - 2008q2 provide modest support for the operation of the Taylor principle in the long-run assessed on the basis of the real interest rate response to an inflation shock. Indeed, we find that the imposition of Taylor's parameter estimates cannot be rejected by the log-likelihood ratio statistic over this sample period. We note, however, that the degree of policy inertia measured in real terms is considerable in the wake of an inflation shock, with a lag of almost four years prior to the emergence of a stabilising real interest rate response. By contrast, we find that the real interest rate has responded rapidly and strongly to the output gap on average during our sample period.

Estimation across rolling windows reveals that the inflation and output gap preferences of Federal Reserve policymakers have exhibited profound shifts during our sample period. In general, our results suggest that the Fed often adhered to the Taylor principle prior to the Volcker era while also responding robustly to output gap shocks. Under Volcker, the Fed pursued aggressive anti-inflationary policies and the Taylor Principle was upheld at all times. On the other hand, the policy response to the output measured in real terms was relatively weak at this time. Finally, since the Great Moderation, we find that monetary policy has become less aggressive in combating inflation and has focused increasingly on correcting output gap disequilibria. The result is that we do not observe the operation of the Taylor Principle in this period.

We attribute the observation that the Taylor Principle has not been upheld during the Great Moderation to the globalisation of product markets, which has created a series of beneficial supply shocks and has thereby restrained inflationary pressures in many industrialised countries. This has allowed the Fed to pursue growth-promotion in recent years with little concern for the inflationary consequences. By employing a novel decomposition of the nominal interest rate impulse response functions with respect to inflation and output shocks, we find that the long-run effect of demand-side shocks has weakened since the onset of the Great Moderation while the reverse pattern characterises the case of supply-side shocks. This observation is again consistent with the notion that the stability observed under Greenspan was in large part the result of the disinflationary effect of globalisation. In such an environment, the Fed has not normally found it necessary to raise rates aggressively to combat inflationary pressures. In this respect, our results are consistent with Greenwood-Nimmo, Shin and Van Treeck (2010) which contends that the apparent success of monetary policy in the Great Moderation era was largely the result of a favourable macroeconomic climate.

The paper proceeds in 5 sections. Section 2 critically reviews the existing single-equation based modelling techniques that have been applied in the analysis of Taylor's rule. Section 3 discusses the issues raised by estimation in the presence of mixed $I(0)$ and $I(1)$ series and contains a careful derivation of our system model. Section 4 presents the results of single-equation and system estimation, both over the full sample and on a rolling basis. Finally, section 5 offers some concluding remarks.

2 Static and Dynamic Representations of Taylor's Rule

Taylor (1993) proposes a simple instrument rule to explain monetary policymaking in the early years of Alan Greenspan's chairmanship of the Federal Reserve. This rule takes the following form:

$$i_t = r^* + \pi_t + \beta_\pi (\pi_t - \pi^*) + \beta_y y_t \tag{2.1}$$

where i_t denotes the Federal funds rate, r^* the time-invariant equilibrium real rate of interest, π_t the rate of price-level inflation, π^* the (constant) targeted rate of inflation and y_t the output gap, defined as the deviation of achieved output from potential output in percentage terms[2]. In his seminal article, Taylor assumes that $r^* = 2\%$, $\pi^* = 2\%$ and that the rate of growth of potential output is time-invariant at 2.2%. Moreover, Taylor notes that the imposition of $\beta_\pi = \beta_y = 0.5$ results in a rule that fits US data between 1987 and 1992 remarkably well.

Since the publication of Taylor's paper, his simple specification has gained prominence in the analysis of monetary policymaking in both industrialised and emerging economies. This success can be attributed largely to its intuitive appeal and tractability or, somewhat less charitably, to Taylor's "gross simplification of reality" (Davig and Leeper, 2005, p. 2). This very simplicity has led to the development of an expansive literature based on the premise that Taylor's rule is misspecified in a variety of ways. The proposed modifications to the original model include the development of forward-looking models (*e.g.* Clarida, Galí and Gertler, 2000), the inclusion of a broader range of macroeconomic indicators (*e.g.* Siklos, Werner and Bohl, 2004) and the use of real-time data (*e.g.* Orphanides, 2000). However, perhaps the most commonplace and easily pursued modification is the inclusion of the lagged terms and dynamics required to model inertial policymaking.

The static Taylor rule in (2.1) is likely to be mis-specified owing to its omission of dynamic terms and the presence of pronounced serial correlation (Judd and Rudebusch, 1998; Clarida, Galí and Gertler, 2000; English, Nelson and Sack, 2000; Castelnuovo, 2003). This observation has led to the development of partial adjustment models of the following form characterising inertial interest rate setting:

$$i_t = \delta \left\{ \pi_t + r^* + \beta_\pi (\pi_t - \pi^*) + \beta_y y_t \right\} + (1 - \delta) i_{t-1}, \tag{2.2}$$

where $0 \leq \delta \leq 1$ is the adjustment speed. Among the studies mentioned above, estimates of δ are typically of the order of 0.25. Dynamic modelling of this type has at least two important implications. Firstly, it suggests that policymakers act in a gradual fashion, perhaps due to deliberate interest rate smoothing (Goodfriend, 1987) or due to their uncertainty over the dynamic structure of the economy (Sack, 1998, 2000). Secondly, and importantly, if the dynamic form is closer to the true unobserved data generating process, then estimation of the static form will be severely biased (Pesaran and Shin, 1998).

It is possible to analyse the implications of the value taken by δ in a more formal manner by re-writing (2.1) and (2.2) as they are typically estimated:

$$i_t = \alpha + \beta_\pi \pi_t + \beta_y y_t, \tag{2.3}$$

$$i_t = a_0 + \phi_1 i_{t-1} + \theta_\pi \pi_t + \theta_y y_t, \tag{2.4}$$

where $\alpha = r^* - \beta_\pi \pi^*$, $\phi_1 = 1 - \delta$, $a_0 = \delta\alpha = (1 - \phi_1)\alpha$, $\theta_\pi = \delta\beta_\pi = (1 - \phi_1)\beta_\pi$, and $\theta_y = \delta\beta_y = (1 - \phi_1)\beta_y$. Assuming, as Taylor did, that both r^* and π^* are constant and can be estimated by the intercept, then our prior belief is that $\beta_\pi > 1$ (*i.e.* the Taylor principle holds) and that $\beta_y \geq 0$.

[2]Laubuch and Williams (2003) provide empirical support for the notion of a time–invariant natural rate of interest in the US. However, the constancy of both the natural rate of interest and that of the inflation target has been strongly challenged by Woodford (2001), who argues that the natural rate of interest is likely to be time-varying and that, in such a setting, the inflation target should track it. Indeed, the notion of a variable inflation target has recently been explored in terms of 'trend inflation' targeting (*e.g.* Raggi, Greco and Castelnuovo, 2008). However, the assumed constancy of both r^* and π^* herein represents the most commonly studied case and reflects the operating procedures of many modern central banks, which tend to adopt a fixed point or band target. Even in the case where both are time-varying, if π^* closely tracks r^*, then the intercept, $\alpha = r^* - \beta_\pi \pi^*$, can be treated as time-invariant without loss of generality. We will leave the more general case for future research.

From (2.4), it is easily seen that the long-run coefficients on inflation and the output gap may be computed as $\beta_\pi = \theta_\pi / (1 - \phi_1)$ and $\beta_y = \theta_y / (1 - \phi_1)$. Hence, the magnitude of the coefficient on the lagged interest rate term is clearly related to the strength with which monetary policymakers have responded to inflation and the output gap[3]. As δ becomes smaller, ϕ_1 approaches unity, implying that the central bank acts in a gradual fashion, striving to reduce the volatility of the interest rate almost to the exclusion of its policy rule[4].

Quite aside from the implications of inertial modelling for the yield curve, it is well-established that estimation of the dynamic form will be biased when there is residual serial correlation in (2.4). This issue is, however, readily resolved by re-casting the model as an ARDL(p, q_1, q_2) model as follows:

$$\Delta i_t = \rho i_{t-1} + \theta_\pi \pi_{t-1} + \theta_y y_{t-1} + \sum_{j=1}^{p} \gamma_{ij} \Delta i_{t-j} + \sum_{j=0}^{q_1} \gamma_{\pi j} \Delta \pi_{t-j} + \sum_{j=0}^{q_2} \gamma_{yj} \Delta y_{t-j} + e_t, \qquad (2.5)$$

where $\rho = \phi_1 - 1$ and $e_t \sim iid\left(0, \sigma_e^2\right)$.

Finally, notice that both the static and dynamic forms of Taylor's rule suffer from a potentially serious shortcoming where one cannot exclude the possibility of non-zero contemporaneous correlation between the regressors and the underlying disturbances. Where both π_t and y_t are $I(1)$, this can be easily removed by applying Phillips and Hansen's (1990) semi-parametric correction to the static form, (2.1), and by applying Pesaran and Shin's (1998) ARDL-based parametric correction to the dynamic form, (2.4)[5]. However, strong theoretical reasons exist to presume that a reliable measure of the output gap should be $I(0)$. In this case, the correction is imperfect, with the extent of its success depending on the degree of persistence of the series concerned. However, in a model combining persistent and stationary variables, it is likely that the endogeneity of stationary variates will be of secondary importance relative to the endogeneity of persistent variates[6].

The range of considerations and concerns outlined above collectively suggest a general and severe reservation about much of the existing empirical literature employing single equation

[3]This discussion of the long-run coefficients associated with dynamic estimation leads us to a further shortcoming of much of the existing empirical literature. It has become common practice to compare estimates of β_π and θ_π on a like-for-like basis. However, they measure fundamentally different phenomena. The β parameters of the static model capture the long-run relationship between the interest rate and its covariates. By contrast, the θ parameters from the dynamic form essentially capture the short-run response of the interest rate to fluctuations in these covariates. Hence, it is the long-run coefficients from dynamic estimation that should be compared with those estimated from the static form.

[4]The specification of dynamic instrument rules is not, however, uncontroversial. Rudebusch (2002) argues that the significance of the lagged dependent variable implies a high degree of predictability of the interest rate in a manner inconsistent with practical experience of the yield curve. Furthermore, Consolo and Favero (2009) demonstrate that if a monetary policy rule is recast as a reverse specification in which (future) inflation is the dependent variable (and is therefore not instrumented), then a much lower estimate of monetary policy persistence emerges. By contrast, Mankiw and Miron (1986) demonstrate that interest rate smoothing by the Fed might have led to a lack of short-run interest rate predictability (see also English, Nelson and Sack, 2000; Castelnuovo, 2003; and McCallum, 2005). Depending on the nature of the Fed's trade-off among its inflation and output objectives, its optimal policy may entail the smoothing of nominal interest rates or even setting them close to a random walk. Indeed, as δ becomes increasingly small, the long-run Taylor rule relationship becomes increasingly weak until, in the limiting case in which $\delta \to 0$, the long-run parameters β_π and β_y are no longer defined.

[5]The coefficients on the contemporaneous changes in inflation and the output gap in the ARDL model (2.5), $\gamma_{\pi 0}$ and γ_{y0}, are equal to the sum of the coefficients on the associated level variables (*i.e.* θ_π and θ_y) and the regression correlation coefficients between the error terms in the VAR(p) system $\boldsymbol{z}_t = \sum_{j=1}^{p} \boldsymbol{\Phi}_j \boldsymbol{z}_{t-j} + \boldsymbol{\varepsilon}_t$ (assuming that $p = q_1 = q_2$). See Pesaran and Shin (1998) for details.

[6]Should the endogeneity of the stationary output gap series prove problematic then one may wish to pursue an instrumental variable estimation strategy, although the choice of instruments may be non-trivial raising the possibility of weak instrumentation as discussed in Section 4 below.

static and dynamic modelling. In many cases, the estimation of such models by OLS is likely to be inefficient and, in some cases, even inconsistent. Hence, we echo the conclusion of Carare and Tchaidze (2005) that the majority of existing estimation techniques are inadequate. Where the endogeneity of the output gap is not a serious issue, the ARDL model in (2.5) above will provide reliable inference and a sound basis for simple dynamic analysis by means of cumulative dynamic multipliers (*c.f.* Shin, Yu and Greenwood-Nimmo, 2010).

In the next section, we will derive a new vector error correction model combining the persistent and stationary series of interest in a coherent manner. The resulting model represents the first serious attempt at bridging the $I(0)/I(1)$ gap in a system context and provides a natural vehicle for advanced dynamic analysis which fully incorporates the feedback effects between the three variables in the system in a manner that single equation models are inherently incapable of achieving. Moreover, we will demonstrate that the construction of the model allows one to draw structural inferences on the basis of simple orthogonalised impulse response functions. Lastly, we will conduct a careful decomposition of the resulting interest rate responses to inflation and output gap shocks that can illuminate the underlying causal mechanisms and trace their relative importance across the forecast horizon.

3 A VECM Representation of Taylor's Rule

In addition to the static versus dynamic debate outlined above, a growing number of researchers have studied the apparent imbalance between persistent and stationary series in Taylor-type rules (*c.f.* Siklos and Wohar, 2005). The interest rate and the rate of consumer price inflation are widely believed to follow either $I(1)$ or near integrated processes (c.f. Backus and Zin, 1993; Tkacz, 2001; Henry and Shields, 2004). While Taylor originally defined the output gap by linear de-trending resulting in a trendless $I(1)$ approximation, it has become common practice to define a stationary output gap using more sophisticated detrending techniques or the production function approach (*c.f.* Roeger, 2006).

Consider first the case that $\beta_y = 0$. The presence of multiple $I(1)$ variables raises the possibility of cointegration. Indeed, to the extent that the central bank pursues inflation-targeting monetary policy (*de facto* or otherwise), we might expect the interest rate and inflation to be cointegrated. However, the majority of papers estimating simple Taylor-type rules (and certainly all of those following the simple estimation approaches outlined above) have failed to properly account for the time series properties of the regressors. Österholm (2005) concludes that this is likely to result in inconsistent estimation. More generally, the failure to adequately account for the possibility of cointegration among the variables of interest results in the exclusion of potentially valuable information about the underlying economic relationships.

In the more general case that $\beta_y \neq 0$, one is faced with the challenge of estimating a model in the presence of both $I(1)$ and $I(0)$ variables. Such estimation may be successfully carried out in the single equation case using the ARDL bounds-testing approach advanced by Pesaran, Shin and Smith (2001). However, little progress has been made to date in the system setting, with the exception of the work of Pagan and Pesaran (2008) on permanent and transitory shocks in structural VAR models. Indeed, existing system models have generally circumvented the non-homogeneity of the time series properties of the regressors in either of two suboptimal ways. Firstly, a number of authors have replaced the stationary output gap with either the level of output or the unemployment gap relative to the NAIRU, thereby achieving an homogeneous $I(1)$ specification (an example of the latter is Ball and Tchaidze, 2002)[7]. Secondly, many studies consider the model re-cast in first differences (a notable example is English, Nelson and

[7]Giordani (2004) contends that the use of the level of output in place of the output gap may generate the frequently observed price puzzle, where inflation overshoots in the short-run following an interest rate innovation.

Sack, 2003), thereby abstracting altogether from such long-run issues and losing the information contained in the levels of the data.

We attempt to contribute to this literature by deriving a simple system of equations for $i_t \sim I(1)$, $\pi_t \sim I(1)$ and $y_t \sim I(0)$. We construct the following system of equations (suppressing the intercept for simplicity):

$$i_t = \phi_1 i_{t-1} + \theta_\pi \pi_t + \theta_y y_t + e_{1t}, \tag{3.1}$$

$$\pi_t = \pi_{t-1} + e_{2t}, \tag{3.2}$$

$$y_t = \phi_3 y_{t-1} + e_{3t}, \tag{3.3}$$

where e_{1t}, e_{2t}, and e_{3t} are both contemporaneously and serially correlated. Abstracting for the moment from serial correlation, (3.1)-(3.3) can be re-written as follows:

$$\Delta i_t = \rho_1 i_{t-1} + \theta_\pi \pi_{t-1} + \theta_\pi \Delta\pi_t + \theta_y y_{t-1} + \theta_y \Delta y_t + e_{1t}, \tag{3.4}$$

$$\Delta\pi_t = e_{2t}, \tag{3.5}$$

$$\Delta y_t = \rho_3 y_{t-1} + e_{3t}, \tag{3.6}$$

where $\rho_1 = (\phi_1 - 1)$ and $\rho_3 = (\phi_3 - 1)$. Note that the construction of (3.5) and (3.6) simply states that inflation is $I(1)$ and the output gap $I(0)$ by construction. It may be interesting to consider the case in which inflation is modelled as an $I(0)$ process, its evolution depending on a number of covariates (*e.g.* the output gap, wage inflation, import price inflation *etc.*). This is clearly a straightforward modification of the system but our interest at present is to model the simple dynamic form of Taylor's rule under a set of common assumptions.

Combining (3.4)-(3.6), we can re-cast the system as a VAR model as follows:

$$\boldsymbol{A}_0 \Delta \boldsymbol{z}_t = \boldsymbol{\alpha}_0 \boldsymbol{\beta}' \boldsymbol{z}_{t-1} + \boldsymbol{e}_t, \tag{3.7}$$

where

$$\begin{aligned} \boldsymbol{z}_t &= \begin{bmatrix} i_t \\ \pi_t \\ y_t \end{bmatrix};\ \boldsymbol{A}_0 = \begin{bmatrix} 1 & -\theta_\pi & -\theta_y \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix};\ \boldsymbol{\alpha}_0 = \begin{bmatrix} \rho_1 & 0 \\ 0 & 0 \\ 0 & \rho_3 \end{bmatrix}; \\ \boldsymbol{\beta}' &= \begin{bmatrix} 1 & -\beta_\pi & -\beta_y \\ 0 & 0 & 1 \end{bmatrix};\ \boldsymbol{e}_t = \begin{bmatrix} e_{1t} \\ e_{2t} \\ e_{3t} \end{bmatrix}. \end{aligned} \tag{3.8}$$

and where $\boldsymbol{\beta}$ is the exactly-identified long-run matrix combining Taylor's rule as one cointegrating relationship and the stationary output gap as the other. Equivalently, (3.7) can be written as a first order reduced-form VECM:

$$\Delta \boldsymbol{z}_t = \boldsymbol{\alpha} \boldsymbol{\beta}' \boldsymbol{z}_{t-1} + \boldsymbol{\varepsilon}_t, \tag{3.9}$$

where

$$\boldsymbol{\alpha} = \begin{bmatrix} \rho_1 & \theta_y \rho_3 \\ 0 & 0 \\ 0 & \rho_3 \end{bmatrix}; \ \boldsymbol{\varepsilon}_t = \begin{bmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \\ \varepsilon_{3t} \end{bmatrix} = \begin{bmatrix} e_{1t} + \theta_\pi e_{2t} + \theta_y e_{3t} \\ e_{2t} \\ e_{3t} \end{bmatrix}.$$

Hence, the Taylor rule can be written as a cointegrating VAR with the following two long-run relationships:

$$\xi_{1t} = i_t - \beta_\pi \pi_t - \beta_y y_t, \tag{3.10}$$

$$\xi_{2t} = y_t. \tag{3.11}$$

The output gap, y_t, is trivially stationary while ξ_{1t} allows us to combine both $I(1)$ and $I(0)$ variables in the long-run relationship (implying that i_t and π_t are cointegrated). In this form, the system can be readily estimated using the long-run structural method advanced by Pesaran and Shin (2002) and GLPS.

The above derivation adheres to the simplistic assumption typical of the literature on the inertial Taylor rule that the the dynamics can be captured by a first-order autoregressive process (*c.f.* Judd and Rudebusch, 1998; English, Nelson and Sack, 2003). However, this assumption is likely to be excessively restrictive, particularly when one considers that the Federal funds rate often remains constant for many consecutive months. We now generalise this discussion to the case of serially correlated structural errors. To this end, we consider the system of equations, (3.1)-(3.3), and assume that $\boldsymbol{e}_t$ follows the VAR(1) process[8]:

$$\boldsymbol{e}_t = \boldsymbol{B}\boldsymbol{e}_{t-1} + \boldsymbol{u}_t, \tag{3.12}$$

where $\boldsymbol{u}_t \sim iid\,(\mathbf{0}, \boldsymbol{\Sigma})$ and $\boldsymbol{B} = \begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{bmatrix}$.

Premultiplying (3.7) by $(\boldsymbol{I}_3 - \boldsymbol{B}L)$ and rearranging yields:

$$\boldsymbol{A}_0 \Delta \boldsymbol{z}_t = (\boldsymbol{I}_3 - \boldsymbol{B})\,\boldsymbol{\alpha}_0 \boldsymbol{\beta}' \boldsymbol{z}_{t-1} + \left(\boldsymbol{B}\boldsymbol{\alpha}_0\boldsymbol{\beta}' + \boldsymbol{B}\boldsymbol{A}_0\right)\Delta \boldsymbol{z}_{t-1} + \boldsymbol{u}_t, \tag{3.13}$$

which can be written as the second order reduced-form VECM:

$$\Delta \boldsymbol{z}_t = \boldsymbol{\alpha}\boldsymbol{\beta}' \boldsymbol{z}_{t-1} + \boldsymbol{\Gamma}\Delta \boldsymbol{z}_{t-1} + \boldsymbol{\varepsilon}_t, \tag{3.14}$$

where

$$\boldsymbol{\alpha} = \boldsymbol{A}_0^{-1}(\boldsymbol{I}_3 - \boldsymbol{B})\,\boldsymbol{\alpha}_0; \ \boldsymbol{\Gamma} = \boldsymbol{A}_0^{-1}\left(\boldsymbol{B}\boldsymbol{\alpha}_0\boldsymbol{\beta}' + \boldsymbol{B}\boldsymbol{A}_0\right); \ \boldsymbol{\varepsilon}_t = \boldsymbol{A}_0^{-1}\boldsymbol{u}_t = \begin{bmatrix} u_{1t} + \theta_\pi u_{2t} + \theta_y u_{3t} \\ u_{2t} \\ u_{3t} \end{bmatrix}.$$

Notice that:

$$\begin{aligned} \boldsymbol{\alpha} &= \begin{bmatrix} 1 & -\theta_\pi & -\theta_y \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 - B_{11} & B_{12} & B_{13} \\ B_{21} & 1 - B_{22} & B_{23} \\ B_{31} & B_{32} & 1 - B_{33} \end{bmatrix} \times \begin{bmatrix} \rho_1 & 0 \\ 0 & 0 \\ 0 & \rho_3 \end{bmatrix} \\ &= \begin{bmatrix} (1 - B_{11})\,\rho_1 + \theta_\pi B_{21}\rho_1 + \theta_y B_{31}\rho_1 & B_{13}\rho_3 + \theta_\pi B_{23}\rho_3 + \theta_y (1 - B_{33})\,\rho_3 \\ B_{21}\rho_1 & B_{23}\rho_3 \\ B_{31}\rho_1 & (1 - B_{33})\,\rho_3 \end{bmatrix}. \end{aligned}$$

[8] This represents the most general case in which we allow for correlation between the structural disturbances. In practice, it may be desirable to impose a diagonal structure on the matrix $\boldsymbol{B}$, in keeping with the approach commonly adopted in the structural VAR literature.

It is clear that none of the elements of the error correction matrix, $\boldsymbol{\alpha}$, in (3.14) are pre–specified to be zero unless the VAR(1) parameter matrix, $\boldsymbol{B}$, is diagonal, in which case $\boldsymbol{\alpha}$ simplifies to:

$$\boldsymbol{\alpha} = \begin{bmatrix} (1 - B_{11})\,\rho_1 & \theta_y\,(1 - B_{33})\,\rho_3 \\ 0 & 0 \\ 0 & (1 - B_{33})\,\rho_3 \end{bmatrix}.$$

In the more general case in which the $\boldsymbol{e}_t$'s in (3.7) follow the VAR$(p-1)$ process:

$$\boldsymbol{e}_t = \sum_{j=1}^{p-1} \boldsymbol{B}_j \boldsymbol{e}_{t-j} + \boldsymbol{u}_t, \tag{3.15}$$

where $\boldsymbol{u}_t \sim iid\,(\boldsymbol{0}, \boldsymbol{\Sigma})$, it is straightforward to derive the associated reduced-form VECM(p):

$$\Delta \boldsymbol{z}_t = \boldsymbol{\alpha}\boldsymbol{\beta}' \boldsymbol{z}_{t-1} + \sum_{j=1}^{p-1} \boldsymbol{\Gamma} \Delta \boldsymbol{z}_{t-j} + \boldsymbol{\varepsilon}_t. \tag{3.16}$$

Hence, the system of three equations for i_t, π_t and y_t, including the Taylor rule as a long-run relationship, may be written in the form of the generic vector error correction model, (3.16). Indeed, this is an appealing combination of the underlying economic theory and a flexible econometric technique. Most importantly, this approach allows us to incorporate the stationary output gap series into the long-run structural VAR framework and provides a more general framework for the analysis of policy inertia and the dynamic relationships between the interest rate, inflation and the output gap than the existing class of dynamic models. In particular, as a system model, it fully accounts for the feedback effects between the three variables in a manner of which single equation models are inherently incapable.

3.1 Long-Run Identification

In practice, VEC models may be estimated in two steps. The long-run structure is estimated in the first step by maximum likelihood and then the associated dynamics are estimated by OLS in the second step. In order to uniquely identify each of the cointegrating vectors, one must impose at least the r^2 restrictions on $\boldsymbol{\beta}$ necessary for its exact identification. Typically, these restrictions should be comprised of at least r restrictions on each of the r columns of $\boldsymbol{\beta}$ in order to satisfy the classical order condition derived by Pesaran and Shin (2002). However, while the theoretical derivation in (3.8) provides for a total of r^2 restrictions on $\boldsymbol{\beta}$ (with $r = 2$) given by

$$\boldsymbol{R\theta} = \boldsymbol{f}, \tag{3.17}$$

where $\boldsymbol{\theta} =$ vec$(\boldsymbol{\beta})$ and

$$\boldsymbol{R} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \ \boldsymbol{f} = \begin{bmatrix} -1 \\ 0 \\ 0 \\ -1 \end{bmatrix},$$

they fail to satisfy the order condition as we impose three restrictions on one cointegrating vector but just one on the other. This structure is necessary in order to model the stationarity of the output gap while allowing for free estimation of the parameters of the Taylor rule. In this case, the identification failure can be demonstrated simply as follows. Pesaran and Shin (2002) show that the $\boldsymbol{\beta}$ matrix subject to the theory-led exact long-run identification scheme in (3.8) can be obtained simply by the following transformation:

$$\hat{\boldsymbol{\theta}} = \left(\boldsymbol{I}_2 \otimes \hat{\boldsymbol{\beta}}_{JO}\right) \left[\boldsymbol{R}\left(\boldsymbol{I}_2 \otimes \hat{\boldsymbol{\beta}}_{JO}\right)\right]^{-1} \boldsymbol{f} \tag{3.18}$$

where$\boldsymbol{I}_2$ is a 2×2 identity matrix, and $\hat{\boldsymbol{\beta}}_{JO}$ is the Johansen eigen-vectors. However, given the singularity of $\boldsymbol{R}\left(\boldsymbol{I}_2 \otimes \hat{\boldsymbol{\beta}}_{JO}\right)$ under (3.17) the unique estimation of $\hat{\boldsymbol{\beta}}$ is not generally feasible. To avoid the rank deficiency problem, we could employ the generalised inverse of $\boldsymbol{R}\left(\boldsymbol{I}_2 \otimes \hat{\boldsymbol{\beta}}_{JO}\right)$, thereby obtaining approximate estimates of $\boldsymbol{\beta}$ subject to (3.17).[9]. In practice, however, we find that this yields a non-unique transformation.

One possible means of achieving a unique factorisation of $\boldsymbol{\Pi} = \boldsymbol{\alpha}\boldsymbol{\beta}'$ is to impose additional identifying restrictions on the loading matrix, $\boldsymbol{\alpha}$. Our derivation of the model provides a theoretical justification for three zero restrictions on $\boldsymbol{\alpha}$ under the assumption that $\boldsymbol{B}$ in (3.12) is diagonal[10]. In principle, estimation subject to joint restrictions of this nature can be carried out using Boswijk's (1995) switching algorithm. However, in practice, we encounter two difficulties. Firstly, the imposition of these restrictions would imply that inflation dynamics do not respond to the output gap or that output gap dynamics do not respond to the policy decisions of the central bank. Moreover, at a more general level, the imposition of restrictions on $\boldsymbol{\alpha}$ may be inadvisable if one believes the relevant short-run economic theory to be somewhat more tentative than the long-run theory. Secondly, we find that estimation in the presence of identifying joint restrictions is highly sample-sensitive and often results in non-convergence, even under very loose convergence criteria.

Given the existing class of algorithms used to factorise $\boldsymbol{\Pi}$, it is, therefore, not possible to achieve the first best solution of estimating the parameters of the long-run matrix subject to the unbalanced theoretical restrictions within the VECM framework.[11] By contrast, it is straightforward to estimate the model dynamics in the usual manner subject to a given value of $\boldsymbol{\beta}$. This can be derived from either of two sources. Firstly, we may simply impose theory led values of the long-run parameters, β_π and β_y, perhaps the most obvious candidates being Taylor's original coefficient estimates. Secondly, we may estimate these long-run parameters in an auxiliary regression. A variety of auxiliary regression models present themselves, although the obvious choice is the ARDL model described by (2.5) above. Not only does the ARDL model approximate the functional form of the interest rate equation in the cointegrating VAR model but it represents the most robust single equation estimation technique considered in Section 2, above. Moreover, we find that, in practice, although the results of the transformation of the Johansen $\boldsymbol{\beta}$ discussed above are not unique, they are typically qualitatively similar to the long-run coefficients derived from the single equation ARDL model. The comparison is particularly close when we set the lag length of the ARDL model to match that of the VECM[12].

---

[9]We cannot use $\hat{\boldsymbol{\beta}}_{JO}$ simply because this would preclude the imposition of the stationarity of the output gap in the long-run. This, in turn, would undermine the structure of the model and the structural decomposition of the OIRs that we will derive in the next section.

[10]If the rank of $\boldsymbol{\Pi}$ is r, then $\boldsymbol{\Pi}$ is subject to $(m-r)^2$ non-linear restrictions and is, therefore, determined uniquely in terms of the $\left(2mr - r^2\right)$ underlying unknown parameters.

[11]The modelling strategy derived above provides a further challenge to the econometrician. It follows intuitively from the theoretical restrictions imposed on the long-run matrix, $\boldsymbol{\beta}$, that the maximum value of the log-likelihood function is invariant to the value taken by the parameter β_y. This effect results directly from the stationarity of y_t. Given any selected value of β_π, the optimisation algorithm simply circles on an infinitely large plateau of equally likely values of β_y. In order to verify this finding, we conducted a search over the grid set $\{\beta_\pi : 0 \leq \beta_\pi \leq 3\}$ and $\{\beta_y : 0 \leq \beta_y \leq 3\}$. The results are available on request.

[12]In principle, one could consider employing some form of model averaging technique in order to reduce the dependence of the results on the chosen specification of the auxiliary regression.

We opt to proceed by pursuing both strategies, and estimate the model subject to the following two distinct sets of long-run restrictions:

$\boldsymbol{\beta}_{LR}$: Imposition of the ARDL long-run coefficient estimates for β_π and β_y; and

$\boldsymbol{\beta}_{TR}$: Imposition of Taylor's coefficients, *i.e.* $\beta_\pi = 1.5$ and $\beta_y = 0.5$.

We view the imposition of $\boldsymbol{\beta}_{LR}$ as the most data-driven option available to us and, as such, the option that is likely to provide the most reliable inference. By contrast, the imposition of $\boldsymbol{\beta}_{TR}$ can be considered a counterfactual exercise, exploring what would have happened if the Fed had pursued Taylor's strategy in a binding fashion in the long-run. It should be clear, however, that we have little reason to believe that this is an accurate description of how the Fed has in fact acted between 1964q1 and 2008q2 or indeed in many of the sub-periods within this sample.

3.2 Structural Inference and Impulse Response Analysis

Among the principle advantages of system models relative to single equation models is their ability to capture feedback effects between the variables of the system. Moreover, VAR models provide a natural vehicle for sophisticated dynamic analysis owing to their simple autoregressive structure. Due to its unique construction combining both persistent and stationary variables, our VEC model possesses a further valuable attribute: in many cases we are able to draw structural inferences on the basis standard orthogonalised impulse response functions even in the absence of any restrictions on the contemporaneous matrix $\boldsymbol{A}_0$.

It is apparent from equations (3.9) and (3.14) that the reduced-form inflation and output gap shocks are precisely equal to their structural counterparts. By contrast, reduced-form shocks to the interest rate equation, ϵ_{1t}, are an agglomeration of the structural interest rate shocks, e_{1t}, and a linear combination of the structural shocks to the inflation and output gap equations (e_{2t} and e_{3t}, respectively). While it would be possible to disentangle these effects with knowledge of the parameters θ_π and θ_y, this would require a structural factorisation of the contemporaneous matrix $\boldsymbol{A}_0$. Any such factorisation would be subject to the criticism of all structural models regarding their excessive reliance on a limited number of deep parameters (GLPS). The focus of this paper is, however, not on the effect of monetary policy shocks on the interest rate and its covariates. Rather, our interest is in assessing the means by which monetary policy has been set in relation to inflation and the output gap. Hence, we are able to draw structural inferences from our model in relation to these cases of interest due to the stationarity of y_t reflected in the $(0, 0, -1)$ cointegrating vector imposed within $\boldsymbol{\beta}$.

Some discussion of the interpretation of the orthogonalised (structural) impulse response functions (IRFs) is in order given the novelty of our modelling framework. It is well known that shocks exert only a temporary effect in stationary systems. By contrast, this is not the case in cointegrated systems, where shocks to $I(1)$ variables can have non-zero long-run effects. Nevertheless, the impact of shocks on the cointegrating vectors must asymptote to zero as these vectors are simply stationary linear combinations of the underlying persistent variables. Hence, the long-run properties of the impulse response functions in our specification are somewhat unusual, and warrant some further elaboration.

Consider the IRFs of the interest rate with respect to inflation and output gap shocks, respectively. Recall that we specify two stationary long-run relationships among three variables, $i_t \sim I(1)$, $\pi_t \sim I(1)$ and $y_t \sim I(0)$, as $\xi_{1t} = y_t$ and $\xi_{2t} = i_t - \beta_\pi \pi_t - \beta_y y_t$. These can be readily combined into the following expression:

$$i_t = \beta_\pi \pi_t + \beta_y y_t + \xi_{2t}. \tag{3.19}$$

Defining the h-step ahead IRFs of the variable $x = (i, \pi, y)$ with respect to inflation and output gap shocks as $R_h^{(x,\pi)}$ and $R_h^{(x,y)}$ for $h = 0, 1, 2, ...$, the IRFs of the interest rate with respect to inflation and output gap shocks can be expressed using (3.19) as:

$$
\begin{aligned}
R_h^{(i,\pi)} &= \beta_\pi R_h^{(\pi,\pi)} + \beta_y R_h^{(y,\pi)} + R_h^{(\xi_2,\pi)} \\
&= \beta_\pi R_h^{(\pi,\pi)} + \beta_y R_h^{(\xi_1,\pi)} + R_h^{(\xi_2,\pi)},
\end{aligned} \tag{3.20}
$$

$$
\begin{aligned}
R_h^{(i,y)} &= \beta_\pi R_h^{(\pi,y)} + \beta_y R_h^{(y,y)} + R_h^{(\xi_2,y)} \\
&= \beta_\pi R_h^{(\pi,y)} + \beta_y R_h^{(\xi_1,y)} + R_h^{(\xi_2,y)}.
\end{aligned} \tag{3.21}
$$

Let us first consider the situation in the long-run. As $h \to \infty$, it follows that:

$$R_h^{(\xi_1,\pi)}, R_h^{(\xi_2,\pi)}, R_h^{(\xi_1,y)}, R_h^{(\xi_2,y)} \to 0$$

and thus (3.20) and (3.21) become:

$$R_\infty^{(i,\pi)} = \beta_\pi R_\infty^{(\pi,\pi)},\ R_\infty^{(i,y)} = \beta_\pi R_\infty^{(\pi,y)},$$

which shows that, in the long-run, the IRFs of the interest rate with respect to inflation and output gap shocks depend solely upon the long-run response of inflation to the respective shocks and upon the parameters β_π and β_y. Our analysis may be enriched by lending these terms an economic interpretation. Firstly, we must beg the reader's indulgence for the assumption that the various shocks that we consider can be conceptualised as either nominal or real shocks. In this framework, it follows that $R^{(\pi,\pi)}$ traces the effect of a nominal shock on the rate of price-level inflation. By contrast $R^{(\pi,y)}$ reflects the inflationary response to a real shock. By analogy, it follows that we can define $R^{(y,y)}$ and $R^{(y,\pi)}$ as the output gap response to real shocks and nominal shocks, respectively (although these must be short- to medium-term phenomena by construction as $y \sim I(0)$)[13].

In general, we expect that $R_\infty^{(\pi,\pi)} > 0$ but we have no firm basis on which to draw inferences regarding the relative magnitude of $R_\infty^{(\pi,\pi)}$ and $R_0^{(\pi,\pi)}$ *ex ante*. We expect that $R_h^{(\pi,y)} > 0$ on the basis of familiar demand-pull explanations of inflation although, again, we have no prior belief about the relative size of $R_\infty^{(\pi,y)}$ and $R_0^{(\pi,y)}$. It is intuitively plausible that $R_0^{(y,y)} > 0$ and it follows that $R_\infty^{(y,y)} = 0$ by construction as $y_t \sim I(0)$. Similarly, we may assume that $R_0^{(y,\pi)} < 0$ as detrimental nominal shocks may depress real economic activity in the short-run. Once again, it must be the case that $R_\infty^{(y,\pi)} = 0$.

The implication of this exercise is that both nominal and real shocks may have permanent effects on the price level and the rate of inflation but that neither type of shock will exert anything other than a temporary effect on economic activity relative to trend. While the latter result follows directly from the definition of the output gap, it does not rule out the possibility that various shocks may exert permanent effects on the level of realised output or the level of

[13] An alternative, although perhaps more controversial nomenclature could be conceived around the notion of demand-side and supply-side shocks. We may assume that $R^{(\pi,\pi)}$ represents direct inflationary pressure resulting from cost-push factors (*i.e.* a detrimental supply shock). Similarly, but much less controversially, we may argue that $R^{(\pi,y)}$ reflects demand-pull inflationary pressures, whereby excess demand is associated with rapid (and perhaps accelerating) inflation. In terms of a shock to the output gap, $R^{(y,y)}$ traces the time path of a demand shock in the short- to medium-term before it dies out by construction as $y \sim I(0)$. Finally, $R^{(y,\pi)}$ may be interpreted as the effect of a supply shock on output/demand. In this case, a positive inflation shock may reflect a detrimental supply shock, so we might expect the short- to medium-term response of the output gap to be negative.

potential output themselves, merely that the gap between the two should not exhibit excess persistence. Similarly, one of the essential tenets of New Keynesian monetary theory is that effective monetary policy must strive to anchor inflation expectations in order to restrain the development of persistent inflationary pressures and spirals.

Now suppose that the impact effects $R_0^{(\pi,\pi)}$ and $R_0^{(y,y)}$ are normalised to unity, implying that, on impact, an inflation shock (*i.e.* a nominal shock) increases inflation by 1% and an output gap (real) shock raises the output gap by 1%. In this case, (3.20) and (3.21) become:

$$R_0^{(i,\pi)} = \beta_\pi + \beta_y R_0^{(y,\pi)} + R_0^{(\xi_2,\pi)}$$

$$R_0^{(i,y)} = \beta_\pi R_0^{(\pi,y)} + \beta_y + R_0^{(\xi_2,y)}$$

which shows that we will not observe an interest rate response of 1.5% in the very short-run following and inflation shock or of 0.5% following an output gap shock unless $0.5R_0^{(y,\pi)} + R_0^{(\xi_2,\pi)} = 0$ and $1.5R_0^{(\pi,y)} + R_0^{(\xi_2,y)} = 0$, even if we impose that $\beta_\pi = 1.5$ and $\beta_y = 0.5$. There is little reason to believe that either $R_0^{(y,\pi)}$ and $R_0^{(\xi_2,\pi)}$ or $R_0^{(\pi,y)}$ and $R_0^{(\xi_2,y)}$ should take opposite signs.

In more general terms, the Taylor principle can be addressed at any horizon by comparing $R_h^{(i,\pi)}$ and $R_h^{(\pi,\pi)}$ directly, where it follows that it holds at each horizon, h, only if $R_h^{(i,\pi)} > R_h^{(\pi,\pi)}$ for $h = 0, 1, 2, \ldots$. Given the construction of our model, we can compute IRFs relating to the real interest rate response to inflation and output gap shocks respectively as

$$R_h^{(r,\pi)} = R_h^{(i,\pi)} - R_h^{(\pi,\pi)} \text{ and } R_h^{(r,y)} = R_h^{(i,y)} - R_h^{(\pi,y)} \tag{3.22}$$

where the superscript r denotes the real interest rate approximated by $r = i - \pi$.

This highlights a very important issue relating to the interpretation of dynamic monetary policy models. The assessment of the Taylor principle is straightforward in the static case - it holds only if the coefficient on inflation in the estimated monetary policy rule is greater than unity. However, in the dynamic case, one can think of the Taylor principle in either the short-run, the long-run or, indeed, across any arbitrary timeframe. In a world of inertial policymaking, one would expect to find that the adjustment following a shock is gradual and that the Taylor principle may not hold in the short-run. This is an issue which has been largely ignored by the existing empirical literature because it is an issue that cannot be investigated in single equation models where the dependent variable is the nominal interest rate. It follows that such models cannot illuminate the dynamic response of inflation to an inflationary shock and, therefore, that they cannot model the dynamic real interest rate response in an adequate manner. The same reasoning can be readily applied to the case of an output gap shock.

4 Estimation Results

Our main interest in this paper lies in applying our new modelling framework to investigate the nature of monetary policymaking in the USA, with a particular focus on the extent to which the Fed has pursued stabilising monetary policy in response to both nominal and real shocks. Note that, in general, a positive association between the real interest rate and inflation and output gap shocks would be considered stabilising, while a negative association would tend to exacerbate the effects of the initial shock.

We shall treat the three single equation models in (2.3), (2.4) and (2.5) above as a benchmark against which to judge our system modelling approach. To this end, we initially estimate both the single equation and system models over the period 1964q2 - 2008q2[14]. One must not, however, lose sight of the fact that the declared operating procedures of the Federal Reserve have changed repeatedly over our sample period. Furthermore, a range of more subtle shifts in the preferences of the Fed regarding inflation and output growth may have occurred (often gradually) depending on the presiding chairman and the membership of the Federal Open Market Committee (FOMC). In light of these changes, any model estimated over a long span of data that does not incorporate some form of regime-switching mechanism can only tell us about the average behaviour of the Fed over the sample period.

Such issues have been approached in the literature by use of a range of regime-switching models (*e.g.* Davig and Leeper, 2005; Kim and Nelson, 2006; Raggi, Greco and Castelnuovo, 2008). However, in this paper, we opt for a more robust rolling estimation technique with a window length of 80 quarters, a figure that our initial experimentation indicates should balance our desire to investigate the richest possible range of regimes with the data requirements of our VEC model. Rolling and recursive analyses of interest rate setting are not without precedent; good examples include Favero (2006) and Fernandez, Koenig and Nikolsko-Rzhevskyy (2008). The advantage of rolling regression relative to other regime-switching models lies in its greater flexibility, as it can capture the time variation of the relationship of interest without imposing any prior beliefs on the timing-varying nature of the data generating process[15].

4.1 Full Sample Estimation

4.1.1 Single Equation Modelling

Full sample estimation results for the three single-equation specifications in (2.3), (2.4) and (2.5) are presented in Table 1. Firstly, the results of the static model suggest that the Taylor principle has not been satisfied on average across the sample and that the monetary policy response to the output gap has been very weak, with the Fed raising the funds rate just 0.065% in response to a 1% positive increase in the output gap. However, as has been widely discussed in the literature on interest rate smoothing, we find that (2.3) suffers from chronic misspecification that induces severe serial correlation and, therefore, that its estimation by OLS will be unreliable. This casts serious doubt on the validity of existing empirical studies employing a similar functional form and suggests that they provide little evidence in relation to the conduct of monetary policy.

TABLE 1 ABOUT HERE

Turning to the dynamic specification, we again observe a sub-unit coefficient on inflation ($\widehat{\beta_\pi} = 0.86$) but the coefficient on the output gap is now considerably larger ($\widehat{\beta_y} = 0.68$) and more consistent with the figures surveyed by Carare and Tchaidze (2005). In order to assess whether the endogeneity of the inflation variable is a serious problem, we estimate the ARDL(1,1) model as this matches the first order dynamic model as closely as possible[16]. In this case, we find evidence in support of the operation of the Taylor principle between 1964q2 and 2008q2,

[14] All required data were retrieved from the IMF's International Financial Statistics. The output gap is computed as a multiple of four times the difference between the logged level of quarterly GDP and its logged trend, defined using the Hodrick-Prescott filter with the smoothing parameter set according to the Ravn-Uhlig frequency rule. Hence, all variables may be interpreted as annual percentages.

[15] This feature of rolling regression is highly attractive considering that full-sample estimation would be vulnerable to time-variation in the persistence of the inflation process and to the flattening of the Phillips curve that many argue has occurred over our sample, phenomena that are often linked to the Great Moderation (O'Reilly and Whelan, 2005; Ihrig *et al.*, 2007).

[16] F_{PSS} denotes the bounds-based F-test of the long-run levels relationship proposed by Pesaran, Shin and Smith (2001). On this basis, we reject the null hypothesis of no levels relationship at the 5% level given the relevant upper bound critical value of 4.85 tabulated by the authors.

with $\widehat{\beta_\pi} = 1.06$ while $\widehat{\beta_y} = 0.65$. The difference between the ARDL(1,1) estimates and those from the standard dynamic model (2.4) suggests that the endogeneity of inflation may indeed be a serious problem in the standard dynamic model, raising the spectre of misleading inference in much of the existing interest rate smoothing literature[17].

We also compute the cumulative dynamic multiplier effects of unit shocks to the dependent variables on the interest rate in the ARDL model following Shin, Yu and Greenwood-Nimmo (2009). The results, presented in Figure 1, indicate that monetary policy has acted relatively gradually over the sample under consideration, taking six quarters to achieve 50% of the traverse to equilibrium following a shock to either the rate of inflation or the output gap. This result is consistent with the findings of Judd and Rudebusch and Clarida *et al.* (2000) that between 10 and 30% of the required adjustment is achieved per quarter. This effect could not be captured by a static model, suggesting that the rich dynamics embedded in our proposed system model may prove highly beneficial. Similarly, this well developed lag structure should successfully overcome the serial correlation resulting from the regularity with which the FOMC reaches a 'no-change' vote, a feat of which the simple first order models estimated here have proven incapable.

FIGURE 1 ABOUT HERE

4.1.2 System Modelling

Using the data-driven parsimonious VAR(3) specification favoured by a variety of model selection criteria, the Johansen maximum eigenvalue and trace statistics reported in Table 2 indicate the existence of two distinct cointegrating vectors among our three variables. Figure 2 presents orthogonalised impulse response functions characterising the response of both nominal and real interest rates to inflation and output gap shocks under each of the long-run identification schemes discussed in Section 3.1[18]. The log-likelihood ratio tests of the over-identifying restrictions imposed in $\boldsymbol{\beta}_{LR}$ and $\boldsymbol{\beta}_{TH}$ record values of just 2.951 and 2.689, respectively. In both cases, these figures are well-below the 95% criticial value of the χ^2_2 distribution. Finally, in order to facilitate the interpretation of the OIRs and to render them broadly comparable to the ARDL-based dynamic multipliers presented in Figure 1, we consider it prudent to re-normalise such that the impact effect of a shock to the j-th equation on the j-th variable is unity (see Section 3.2).

FIGURE 2 ABOUT HERE

The most striking aspect of the OIRs obtained under the respective long-run matrices is their similarity. As with the likelihood ratios reported above, this reflects the similarity of the freely estimated parameters within $\boldsymbol{\beta}_{LR}$ and those imposed in $\boldsymbol{\beta}_{TR}$ across the full sample. Consider first the nominal interest rate response to a positive inflation shock depicted in panel (a). In both cases, we observe a relatively strong, although also relatively gradual, increase in the nominal interest rate in the wake of the shock, with the OIRs converging to long-run values of approximately 1.1. Underlying this policy response, we observe a mild offsetting effect arising in the medium-term through the negative response of the output gap to the inflationary shock as measured by $R_h^{(y,\pi)}$. Furthermore, we find that the inflationary shock exerts a considerable

[17] It would be difficult to correct for potential endogeneity of the stationary output gap as our early experimentation with the use of lagged values of the output gap as instruments yielded disappointing results. This suggests that the output gap may be a weak instrument owing to its modest serial correlation. However, it is likely that the potential endogeneity of the output gap would be of secondary importance relative to the endogeneity of the more persistent inflation series.

[18] Note that the ARDL long-run coefficients imposed in $\boldsymbol{\beta}_{LR}$ are derived from an ARDL(3,3,3) model in this case in order to match the specification of the constituent equations of the VECM as closely as possible.

long-run effect, as $R_h^{(\pi,\pi)}$ initially overshoots from its impact value of 1.0, reaching a peak of approximately 1.4 after 5 quarters before decreasing smoothly and gradually to a long-run value of approximately 0.7 under $\boldsymbol{\beta}_{TR}$ and 0.8 under $\boldsymbol{\beta}_{LR}$[19].

Now consider the real interest rate response shown in panel (c). In light of the dynamic response of inflation to the initial shock, we find that the Taylor Principle defined as $R_h^{(i,\pi)} > R_h^{(\pi,\pi)}$ does not bind in the short-run but is only observed for $h > 14$ under $\boldsymbol{\beta}_{TR}$ and for $h > 15$ under $\boldsymbol{\beta}_{TR}$. This suggests that there is a considerable lag before the Federal Reserve enacts policies that would typically be considered stabilising. This result is not in conflict with the widely held opinion that the inside lag associated with monetary policy is between 3 and 6 months but rather suggests that policymakers may have chosen to act gradually, possibly to smooth the time-path of the interest rate or possibly due to risk aversion under uncertainty. Lastly, we note that, in the long-run, the real interest rate OIR converges to a value approaching 0.35 under both of the respective long-run matrices.

Moving on to the case of an output gap shock, the similarity of the results under the respective long-run matrices is once again remarkable. Panel (b) depicts a rapid nominal interest rate response in a manner eminently consistent with Taylor's rule, with the majority of the adjustment observed within just three quarters. Moreover, our finding that the interest rate increases approximately 0.37% in the long-run in response to a 1% positive output gap shock is generally consistent with the figures presented in much of the existing literature. However, by applying our proposed decomposition of the OIRs, we note that the output gap response to the initial shock measured by $R_h^{(y,y)}$ is strong in the short- to medium-run, overshooting mildly from its impact value of 1.0 before converging to zero after approximately 10 quarters. This induces the rapid initial nominal interest rate response observed in panel (c). Meanwhile, $R_h^{(\pi,y)}$ traces a shape broadly similar to $R_h^{(i,y)}$ but with the upward adjustment occuring somewhat more slowly (the peak value is reached after 8 quarters as opposed to 3). This combination of effects results in the observed pattern of real interest rate adjustment in panel (d) which shows an early peak reflecting the fact that nominal interest rates react more rapidly than inflation to the initial shock. We then observe a trough as $R_h^{(\pi,y)}$ reaches its peak before $R_h^{(r,y)}$ converges upon a long-run value close to 0.12%. That we observe no negative region in $R_h^{(r,y)}$ suggests that the Fed has reacted in a robustly stabilising manner to output gap shocks on average over the period 1964q2 - 2008q2.

Finally, we note that the degree of policy inertia measured in terms of the speed with which the nominal interest rates adjusts following a perturbation is relatively low in the case of an output gap shock but non-negligible in the case of an inflation shock, where the OIRs indicate that it takes approximately 5 quarters to achieve half of the traverse to the new equilibrium level. This finding is broadly comparable to the results of the ARDL(1,1) model. However, in a system model capable of tracing the effect of shocks on the real interest rate, this may not be the most appropriate measure of inertia because it is not the response of the nominal interest rate that is relevant for stabilisation policies but that of the real rate. In this case, we observe that it takes 12 quarters to achieve half of the required adjustment and that the Taylor principle is not observed for even longer than this. Hence, the degree of *real* inertia is considerably greater than the degree of *nominal* inertia. This indicates that previous studies that have focused solely on the speed of adjustment of the nominal interest rate may provide little evidence in relation to the speed with which a stabilising policy stance is attained.

In summary, the results of full sample estimation provide modest support for the operation of the Taylor principle in the long-run, although often with a significant lag. Moreover, we find evidence of a robust stabilising response of the interest rate to non-zero output gaps. However,

[19] While these impulse responses are not reported herein in order to conserve space, they are available on request.

these results represent the average behaviour of the Federal Reserve over a long timeframe and cannot shed any light on the gradual shifts in its preferences and objectives through the years. For this reason, we now consider the results of rolling estimation.

4.2 Rolling Estimation

4.2.1 Single Equation Modelling

Figures 4 and 5 present the results of rolling single equation static and dynamic estimation of Taylor's rule and the associated dynamic multipliers. The vertical lines depict the transition between various chairmen: McChesney Martin Jr. (1951q2 - 1970q1, MCM); Burns and Miller (1970q2 - 1979q3, BUR); Volcker (1979q4 - 1987q3, VOL); Greenspan (1987q3 - 2006q1, GRE); and Bernanke (2006q2 - present, BER). Note that we set a window length of $\omega = 80$ and that the coefficient estimates from window $i = 1, 2, ..., T - \omega$ are plotted at the *end* of the associated rolling sample (*i.e.* window 1 contains observations from 1964q2 to 1984q1 and the estimated coefficients are plotted at 1984q1). One must bear this in mind when attributing effects observed in the figures to a given event or policy regime.

FIGURES 4 & 5 ABOUT HERE

Given the chronic mis-specification of both the simple static and dynamic models we will not linger on the analysis of their results but will merely note that the Taylor principle is only briefly observed for windows ending around the year 2000 (*i.e.* windows starting around 1980) in the static case and is only observed in five distinct windows clustered within this range in the dynamic case.

Moving onto the ARDL model in which we are prepared to place considerably more faith, a striking result emerges: the Taylor principle is observed sporadically in the earlier rolling samples and consistently during the Volcker era but it is conspicuously absent in windows starting after approximately 1982. By contrast, the strongest output gap responses are observed in both the earliest and the most recent rolling samples, with a marked decline in the middle of our sample period (*i.e.* windows starting between approximately 1975 and 1982). These results are generally consistent with the following interpretation. Prior to Volcker, the Fed engaged in quasi-active anti-inflationary policies in conjunction with a robust response to non-zero output gaps. During Volcker's tenure, the Fed became predominantly concerned with inflation and largely neglected the output gap. This period coincides approximately with the onset of the so-called Great Moderation that has been widely discussed in the literature. Finally, under the leadership of Greenspan and Bernanke, and coincident with the continuing stability associated with the moderation, the Fed has not adhered to the Taylor principle in a consistent fashion but has reacted strongly to the output gap. Hence, the results of rolling ARDL analysis suggest that the McChesney-Martin-Burns-Miller era was characterised by a joint concern for inflation and economic growth, the Volcker era was one of strict inflation combating, while the Greenspan-Bernanke era has been dominated by growth-oriented policies.

The relationship between these findings and the existing empirical literature will be explored shortly. For now, we note that our rolling analysis also provides some interesting insights into the nature of the policy response to the ongoing financial crisis. The results suggest that the Bernanke Fed has almost completely abandoned counter-inflationary policies for strongly growth-oriented interventions on a scale not seen at any other time in our sample. Indeed, in the most recent sample period (1988q3 - 2008q2) the estimated long-run coefficient on inflation is, in fact, negative. Striking though these results are, they remain entirely consistent with practical experience of the Fed's management of the financial crisis to date, which has seen aggressive interest rate cuts even (initially at least) in the face of rapid inflationary pressures rooted in spiraling commodity prices. It will be interesting to see whether our system model lends further support to these findings.

Finally, the rolling cumulative dynamic multipliers presented in Figure 5 depict the traverse between a shock to either of the variables entering the reaction function and the long-run interest rate response. In general, the results suggest that the Fed has, on average, made 50% of the required interest rate intervention within the first six quarters after a shock to either variable. However, there is little evidence that the degree of policy inertia measured in nominal terms in this way has varied according to the presiding chairman except in the Volcker era when interest rate smoothing following an inflation shock was considerably less prevalent than it has been at other times. Furthermore, it follows that inertia cannot be meaningfully quantified in those periods when policy failed to respond to specific stimulu robustly (most notably in the middle of our sample in relation to the output gap and toward the end of our sample in terms of inflation). This finding must be interpreted with care due to the simplicity of the dynamics embedded in the ARDL(1,1) model. The more complex lag structure of our VEC model may further light on this issue.

4.2.2 System Modelling

Figure 6 plots the rolling orthogonalised impulse response functions of the nominal interest rate derived under the imposition of $\boldsymbol{\beta}_{LR}$. Consider first the nominal interest rate response to an inflation shock reported in panels (a) and (c). It is clearly evident in the figures that the strongest nominal interest rate response is observed in windows starting between 1975 and 1980, corresponding to Volcker's tenure at the Fed. In these windows, the nominal interest rate response to the inflation shock exceeds 2% in the long-run. Meanwhile, the nominal response to inflation shocks under Greenspan and Bernanke is generally somewhat larger than that enacted by the pre-Volcker Feds in the long-run, of comparable magnitude in the medium-run and noticeably weaker on impact. In neither period do we observe a nominal response consistently exceeding unity at any horizon. However, recall that it is inappropriate to interpret this observation as evidence that the Taylor Principle has not been upheld as we are yet to consider the time path of inflation.

Panels (b) and (d) depict the nominal interest rate response to a positive output gap shock and again reveal a stark change in the behaviour of the Federal Reserve in windows starting after approximately 1981. Prior to this date, we observe a rapid nominal interest rate response to a unit positive output gap shock reaching a value of between 0.4 and 0.5 within the first year and being maintained at a comparable level thereafter. By contrast, in windows starting after 1981, we observe a slightly weaker short-to medium-term nominal response to the initial shock, peaking at approximately 0.3% after 4 quarters and then gradually dying away to insignificance after 14 quarters.

By applying our proposed decomposition of the OIRs, we can scrutinise the effects underlying these nominal interest rate responses and gain some insights into the real interest rate OIRs depicted in Figure 7. Focusing initially on the case of the inflation shock, we observe the largest long-run effect of the inflation shock on inflation as measured by $R^{(\pi,\pi)}$ under Volcker. Similarly, the observed long-run effect is rather large in the post-Volcker period but negligible in the pre-Volcker years[20]. Analysis of $R^{(y,\pi)}$ reveals a non-negligible negative medium-term response of

[20]The finding that an inflation shock exerts a non-negligible long-run effect is unrelated to the persistence of inflation. While persistence can be measured in a variety of ways, it is typically discussed in terms of the degree of autocorrelation exhibited by the inflation series (Fuhrer, 2009). It follows, therefore, that inflationary persistence relates to the process of adjustment from the initial shock to the long-run value and not to the long-run value in itself. Using this intuition, our results support the consensus of opinion that inflation was most persistent pre-Volcker and that it has become markedly less persistent since the onset of the Great Moderation.

the output gap to the inflationary shock in both the pre- and post-Volcker years. Moreover, we find that the effect is somewhat stronger in the former period. This suggests that nominal shocks representing direct inflationary pressures have been partially offset in these periods by a real economic contraction. It is interesting to note that this effect is not apparent in the windows starting between 1975 and 1981 that we have identified most closely with the Volcker Fed. The combination of these effects is manifested in Figures 7(a) and (c) in the observation that the Taylor Principle was robustly upheld in the long-run under Volcker, often upheld pre-Volcker (although not in the earliest rolling windows) but rarely upheld post-Volcker over any horizon.

FIGURES 6 & 7 ABOUT HERE

Conducting the same analysis in relation to the output gap shock, we find that the long-run response of inflation to a positive real shock measured by $R^{(\pi,y)}$ was largest in windows starting between 1974 and 1981 (reflecting the adverse macroeconomic circumstances of the Volcker era) but much smaller in the majority of the remaining windows, with little difference between the pre- and post-Volcker periods. By contrast, the dynamic adjustment of the output gap following the shock shows rapid convergence upon zero, albeit with some mild overshooting in the medium-term in both the pre- and post-Volcker periods. The combination of these factors means that while the nominal interest rate response to the output gap was rather strong under Volcker, the real interest rate response was considerably weaker (Figures 7(b) and (d)), reflecting Volcker's strong anti-inflation preferences. Interestingly, we find that the short- to medium-term policy response in both the pre- and post-Volcker periods is broadly comparable. Moreover, our finding that the real interest rate response to a positive output gap shock is uniformly positive at least at some horizons in all windows indicates that policymakers have generally acted to stabilise output fluctuations between 1964q2 and 2008q2.

Before engaging in a detailed discussion of our findings and teasing out their policy implications, we will briefly summarise the results achieved under the imposition of $\boldsymbol{\beta}_{TR}$. Recall that, in this case, the results can be interpreted as a counterfactual exercise exploring what would have happened if the Fed had followed exactly the prescriptions of the Taylor rule in the long-run. Figure 8 plots the resulting rolling nominal interest rate OIRs. It is interesting to note that the nominal response to inflation and output gap shocks does not change particularly profoundly with the imposition of the new long-run structure. Indeed, the only notable differences are that the nominal interest rate response to inflation is now somewhat larger in the long-run and that the imposition of $\boldsymbol{\beta}_{TR}$ results in somewhat stronger policy responses at all horizons in the earliest few sample windows. However, this apparent similarity of the rolling nominal interest rate OIRs masks some underlying differences that change the pattern of the real interest rate OIRs presented in Figure 9 to a non-negligible degree.

FIGURES 8 & 9 ABOUT HERE

In Figures 9(a) and (c), we consistently observe the operation of the Taylor principle in the long-run by construction. Consulting $R^{(\pi,\pi)}$, we again observe the largest long-run response of inflation to an inflation shock under Volcker but now we note that the long-run pattern observed in the pre-Volcker era has come to closely resemble that of the post-Volcker period. As with the case of $\boldsymbol{\beta}_{LR}$, we again observe a mild offsetting effect arising in the medium-run through the negative response of the output gap to the inflationary shock. Focusing on panels (b) and (d) depicting the real interest rate response to an output gap shock, we see that the implied policy response is somewhat weaker and more volatile than under $\boldsymbol{\beta}_{LR}$. Moreover, notice that the response of the Greenspan-Bernanke Fed to output gap shocks remains largely confined to the short-run even when we impose a long-run coefficient on the output gap of 0.5. The pattern of the underlying inflation and output gap impulse responses is generally similar to the case of $\boldsymbol{\beta}_{LR}$ with the exception that the long-run value of $R^{(\pi,\pi)}$ observed pre-Volcker is now much closer to that observed for windows starting in the Volcker period.

Referring to the rolling likelihood ratio statistics presented in Figure 3, we note that while $\boldsymbol{\beta}_{LR}$ generally achieves a somewhat lower value of the LR statistic than $\boldsymbol{\beta}_{TR}$ due to its data-driven time-varying nature, neither set of restrictions is generally rejected at standard levels of confidence except for windows starting between 1980 and 1982[21]. This region in which the restrictions are not supported by the data coincides with the most intense period of the Volcker disinflation which suggests that the drastic actions taken by the Fed in this period may have caused the prevailing long-run relationships to break down temporarily. Finally, it is interesting to note that the respective rolling LR statistics track one-another quite closely in the more recent windows but even though $\boldsymbol{\beta}_{TR}$ is not rejected in the post-Volcker era, we find little evidence that the Taylor Principle has been upheld during this time based on the more data-driven approach.

Our modelling strategy allows us to separate two different sources of inflationary pressure. $R^{(\pi,\pi)}$ traces the response of inflation to direct inflationary pressure, which may arise as the result of a supply shock, for example. Hence, $R^{(\pi,\pi)}$ may be interpreted in relation to the notion of cost-push inflation. $R^{(\pi,y)}$, on the other hand, measures the response of inflation to a real shock and may, therefore, be interpreted in relation to demand-pull inflation. Therefore, the discussion of $R^{(\pi,\pi)}$ and $R^{(\pi,y)}$ in the preceding paragraph can be interpreted in relation to the changing relative importance of cost-push and demand-pull shocks in the USA. When viewed in this way, our results suggest that the supply-side has come to dominate the inflationary process in the long-run in the USA. This seems intuitively reasonable in light of the increasing liberalisation of trade and the relentless march of globalisation through our sample. This has led to a situation in which demand-side factors may be offset to a large degree by increased supply from overseas trading partners but where inflationary tendencies arising in the supply-side play an increasingly important role in the long-run.

Our finding that the Taylor Principle was not systematically upheld prior to Volcker and that even where it was upheld there was often a very long lag before the enactment of stabilising real interest rate responses that were typically small in magnitude is generally consistent with a large literature on regime-change in US monetary policy (*e.g.* Judd and Rudebusch, 1998; Taylor, 1999; Clarida *at al.*, 2000; Castelnuovo and Surico, 2005). However, our finding that the Taylor Principle has not been upheld post-Volcker is rather striking but is entirely consistent with the results of the ARDL model presented in Figure 5. Moreover, this result may be interpreted in relation to the increasing importance of supply-side considerations during the Great Moderation. If one accepts that the globalisation of product markets has exerted profound disinflationary effects on the US economy on average, then it follows that the Fed may have been able to exploit the associated sequence of positive supply shocks in order to pursue a growth-fostering agenda (it follows from the linearity of our model that a disinflationary shock will result in permanently lower inflation). Indeed, our finding that supply-side shocks have had non-negligible long-run effects on inflation in the post-Volcker period suggests that globalisation may have created a disinflationary ratchet mechanism resulting in the remarkably low rate of inflation during this period.

In his autobiographical monograph *The Age of Turbulence*, Greenspan (2007, pp. 390-1) acknowledges the role of globalisation in the remarkable global disinflation since the early 1980s and argues that it has become increasingly straightforward to achieve growth without accelerating inflation (see also Greenwood-Nimmo, Shin and Van Treeck, 2010). It is perhaps surprising that he maintains a reputation as an inflation hawk despite the fact that, in his own words, "the

[21]Recall, however, that one must interpret these results with care due to the aforementioned invariance of the log-likelihood to the parameter β_y.

best policy...is to go with the flow - to calibrate monetary policy so that it is consistent with global forces. We did that." (p. 390). This policy stance saw remarkably low and stable interest rates in the latter years of Greenspan's tenure, much to the benefit of the financial markets and the real economy (albeit at the cost of inflating a range of nascent bubbles).

The principle difference between the results of the rolling system model and the rolling ARDL model relates to the observed policy response to the output gap in the most recent windows. The dynamic multipliers derived from the ARDL model indicate a very strong nominal interest rate response to the output gap while the OIRs derived from our VEC model indicate a more muted response that is confined largely to the short- to medium-run. However, the observation that the real interest rate OIRs with converge rapidly to zero does not suggest that the policy response has been weak. Rather, this suggests that monetary policy has become somewhat more efficient since the onset of the Great Moderation in the sense that a short-run policy response has proven sufficient to achieve the desired degree of stabilisation. Looking more closely at Figure 7, it appears that the real interest rate response to output gap shocks has been maintained somewhat longer in the last few rolling windows including observations relating to the global economic and financial crisis. This indicates that the Bernanke Fed may indeed have reacted more strongly to output gap disequilibria following the onset of the crisis but the result is not as stark as in the ARDL case.

The observation of an apparent focus on growth-fostering policies reflects Greenspan's (2007) own account of his tenure and is certainly consistent with the record of the Bernanke Fed to date. Furthermore, the combination of growth-orientation and passive anti-inflationary policies is somewhat consistent with the results adduced by Cukierman and Muscatelli (2008). Based on their non-linear framework, the authors show that recession avoidance preferences dominated the Greenspan years, contrary to the common perception of the Greenspan Fed as hawkish toward inflation. Their explanation of this behaviour is slightly different to ours, focusing on the notion that Greenspan inherited price stability from Volcker, granting him remarkable latitude to pursue growth-promotion (p. 19).

Finally, we note that the rolling OIRs indicate considerably more rapid nominal interest rate adjustment than the dynamic multipliers derived from the ARDL model, especially in the case of a shock to the output gap[22]. However, as we have repeatedly argued, it is more appropriate to measure inertia in relation to the time taken for the central bank to achieve stabilising real interest adjustments (*i.e.* the time between the shock and the observation of a positive real interest rate response). In this case, we note considerable inertia under the pre-Volcker Feds following an inflation shock, often of the order of 10 quarters or more. By contrast, under Volcker we observe very little inertia reflecting the aggressive inflation-combating policies of the time. Finally, as we find little evidence that the post-Volcker Feds have adhered to the Taylor Principle, we cannot comment on the degree of inertia measured in this manner. By contrast, in the case of an output gap shock, we note that the degree of policy inertia with respect to the real interest rate is similar across our entire sample.

5 Concluding Remarks

This paper demonstrates that much of the existing empirical evidence concerning Taylor's ubiquitous monetary policy rule is deeply flawed, echoing the view of Carare and Tchaidze (2005).

[22]Interestingly, the nominal interest rate is found to fluctuate mildly in the immediate wake of an inflationary shock, especially prior to Volcker's chairmanship. This may reflect a degree of hesitation on the part of the earlier chairmen to combat nascent inflationary pressures, a reputation that they have certainly gained in subsequent years. This is perhaps an unfair slight on Martin, however, whose hawkish tendencies are documented by Cukierman and Muscatelli (2008, p. 19). These rich dynamic patterns could not be achieved without a well developed dynamic structure, underscoring its importance in monetary policy models.

OLS estimation of both static and dynamic Taylor rules is likely to be both inefficient and inconsistent when the regression errors are serially correlated and/or when the dynamic inertial specification is closer to the true (unobserved) monetary policy reaction function. Moreover, our results indicate that the endogeneity of inflation may compromise the results of many existing studies. A final issue that has been raised in the literature concerns the failure to adequately account for the persistence of the interest rate and inflation series, an omission that may result in spurious regression.

In response to this raft of empirical difficulties, we develop a simple system model of Taylor's rule based on the long-run structural model advanced by Pesaran and Shin (2002) and GLPS. We carefully derive a theory-motivated long-run structure that coherently combines the three series of interest, taking full account of their heterogeneous time series properties. This represents the first serious attempt at combining $I(0)$ and $I(1)$ variates in a system model. Our model has the admirable attribute of all system techniques regarding its ability to properly capture the feedback effects among the variables in the system, providing a firm basis for rich dynamic analysis. By tracing the time-path of both the nominal interest rate and inflation following a shock, we can discuss the dynamic response of the real interest rate. This provides a more appropriate measure of the monetary policy stance as it is the real rate rather than the nominal rate that is relevant for stabilisation policies. Furthermore, the stationarity of the output gap within our system necessitates the imposition of a novel pattern of restrictions within the long-run matrix. We demonstrate that this allows us to draw structural inferences in relation to inflation and output gap shocks on the basis of orthogonalised impulse responses even in the absence of any restrictions on the contemporaneous matrix. Finally, we derive a decomposition of the nominal interest rate IRFs in response to these two shocks that illuminates the underlying causal mechanisms.

The application of our model to the full data sample (*i.e.* 1964q2 - 2008q2) provides modest support for the operation of the Taylor principle in the long-run assessed on the basis of the real interest rate response to an inflation shock. We note, however, that the degree of policy inertia measured in real terms is considerable in this case, with a lag of almost four years prior to the emergence of a stabilising real interest rate response. By contrast, our results indicate that the monetary policy response to the output gap has been rapid and strong on average during our sample period.

In order to assess the shifting preferences of the Federal Reserve over our sample period, we also conduct rolling estimation. In this context, the results provide rich insights into the relative weighting given to the output gap and inflation under various policy regimes. In the single-equation case, our results indicate that the Fed generally adhered to the Taylor principle prior to the Greenspan era. Furthermore, we observe a robust output gap response during this time. With the chairmanship of Alan Greenspan and the occurrence of the Great Moderation, we find that monetary policy shifted focus from inflation to output growth, an effect that we attribute to the disinflationary effect of globalisation on US markets.

Our system model provides comparable results, although the degree of growth-orientation in the post-Volcker period is somewhat less pronounced. By decomposing the nominal interest rate IRFs, we find that the long-run effect of demand-side shocks has weakened since the onset of the Great Moderation while the reverse pattern characterises the case of supply-side shocks. We interpret this as further evidence of the disinflationary effect of globalisation arising through the emergence of a sequence of beneficial supply shocks. On balance, we are persuaded by the weight of evidence suggesting that recent years have seen a shift away from inflation-hawkishness toward growth-orientation among US policymakers. Finally, the results of rolling system estimation suggest that the degree of policy inertia following inflation shocks reduced under Volcker but has otherwise remained relatively constant.

It is appropriate to conclude by noting some of the avenues for further research opened by this paper. Firstly, and perhaps most importantly, our framework could easily be adapted to address a wide range of interesting policy issues. Foremost among these must be the development of a more comprehensive model of the monetary transmission mechanism that could address issues concerning the effect of interest rate innovations on a range of core macroeconomic variables in a coherent manner. It is our hope that such a model may contribute to the resolution of the ongoing debate over the nature of the ubiquitous empirical price puzzle. In addition to the wealth of practical applications of our technique, it also raises a number of interesting econometric issues. Firstly, the development of new computational algorithms for the estimation of VEC models subject to long-run restrictions that fail to satisfy the classical order condition and where the imposition of identifying restrictions on the matrix of loading coefficients is infeasible would be remarkably useful for models such as ours. Similarly, the observed invariance of the log-likelihood to the coefficients associated with stationary variables in mixed $I(0)/I(1)$ systems warrants further attention.

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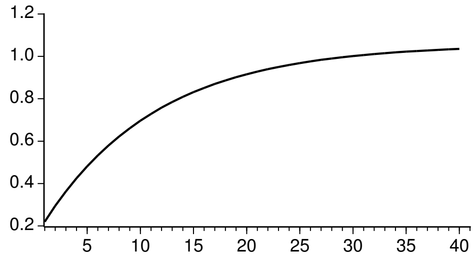
	Static Case		Dynamic Case		ARDL(1,1) Case	
Var.	Coeff.	St.Err.	Coeff.	St.Err.	Coeff.	St.Err.
Const.	2.681	0.311	0.265	0.148	0.127	0.152
π_t	0.814	0.059	0.095	0.033		
y_t	0.065	0.028	0.075	0.011		
i_{t-1}			0.889	0.029	-0.089	0.030
π_{t-1}					0.094	0.034
y_{t-1}					0.058	0.014
$\Delta\pi_t$					0.220	0.118
Δy_t					0.126	0.023
β_π			0.855	0.211	1.057	0.281
β_y			0.676	0.206	0.651	0.246
Adj. R^2	0.537		0.928		0.305	
χ^2_{SC}	148.264[.000]		13.420[.009]		12.638[.013]	
χ^2_{FF}	0.342[.559]		1.676[.196]		0.003[.955]	
χ^2_N	17.854[.000]		733.405[.000]		549.779[.000]	
χ^2_H	5.762[.016]		20.789[.000]		8.601[.003]	
F_{PSS}					8.525	

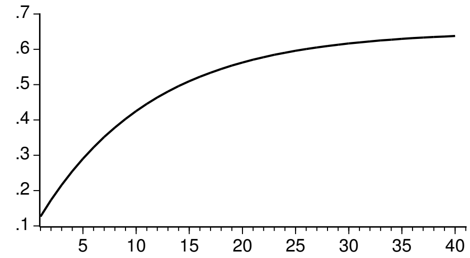
Table 1: Single Equation Estimation of Taylor's Rule

H_0	H_1	Max.	95% cv	90% cv	Trace	95% cv	90% cv
$r = 0$	$r = 1$ / $r \geq 1$	43.238	22.04	19.86	65.678	34.87	31.93
$r \leq 1$	$r = 2$ / $r \geq 2$	14.848	15.87	13.81	22.441	20.18	17.88
$r \leq 2$	$r = 3$	7.593	9.16	7.53	7.593	9.16	7.53

Table 2: Johansen Cointegration Tests

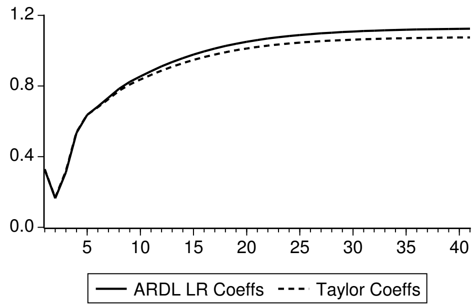


(a) Inflation multiplier

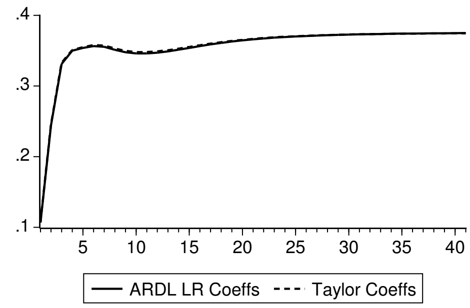


(b) Output gap multiplier

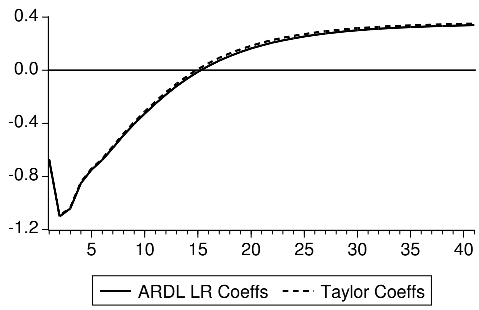
Figure 1: Cumulative Dynamic Multipliers (Full Sample)



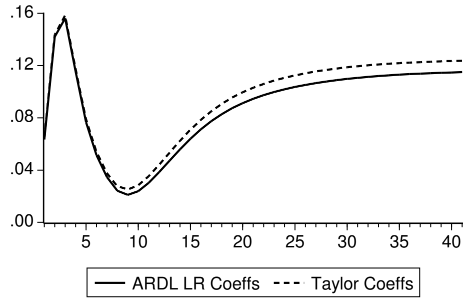
(a) Nominal response to an inflation shock



(b) Nominal response to an output gap shock



(c) Real response to an inflation shock



(d) Real response to an output gap shock

Figure 2: OIRs of Nominal and Real Interest Rates to Specified Shocks (Full Sample)

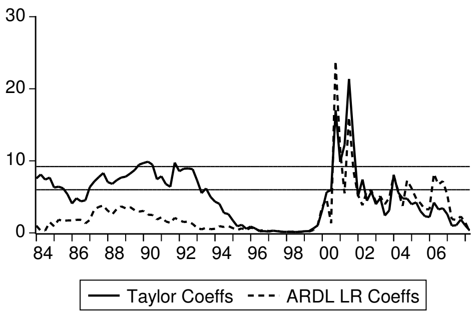
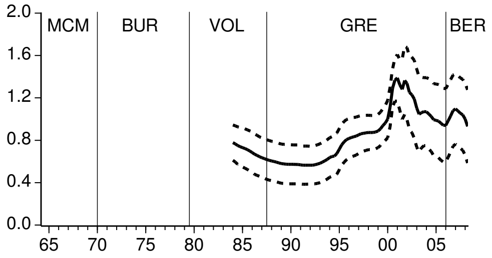
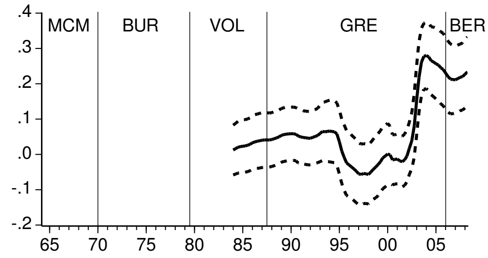


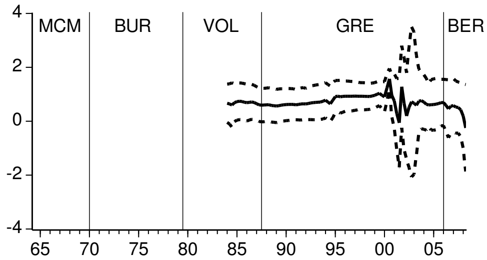
Figure 3: Rolling Likelihood Ratio Statistics relative to χ^2_2 5 and 1% critical values



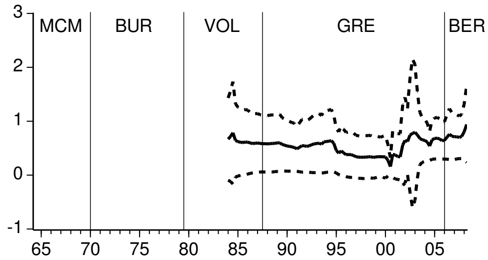
(a) β_π (static)



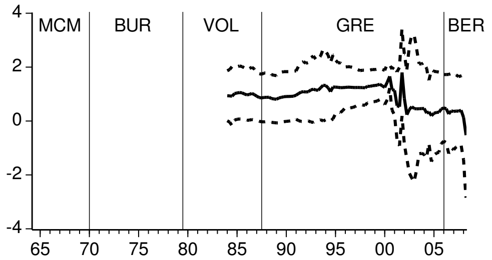
(b) β_y (static)



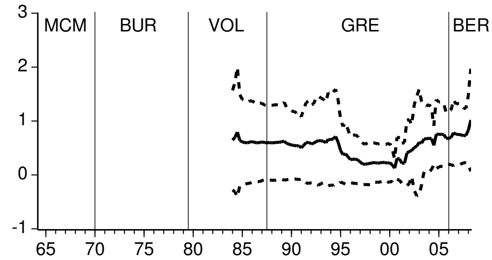
(c) β_π (dynamic)



(d) β_y (dynamic)

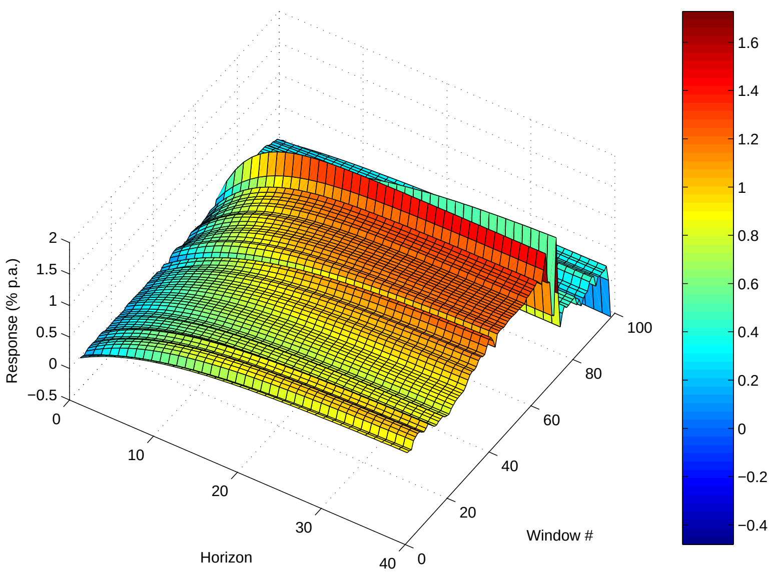


(e) β_π (ARDL)

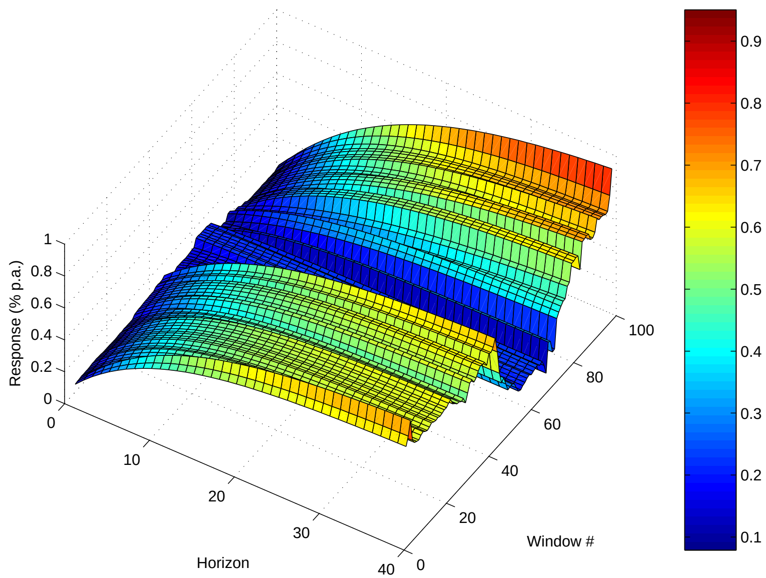


(f) β_y (ARDL)

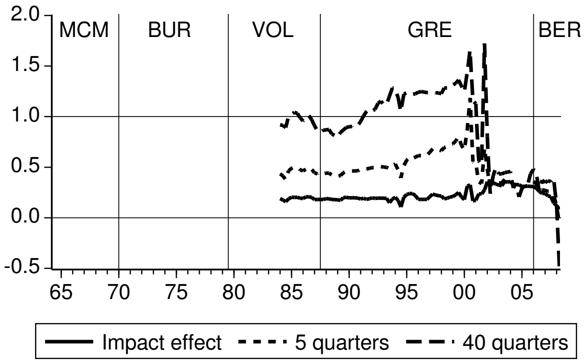
Figure 4: Single Equation Rolling Coefficient Estimates (2SE bands shown as dashed lines)



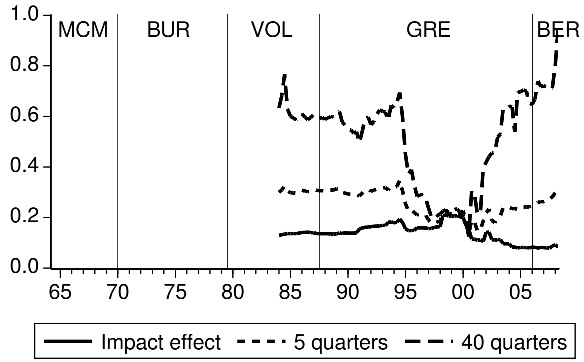
(a) Dynamic multipliers w.r.t. a unit positive inflation shock



(b) Dynamic multipliers w.r.t. a unit positive output gap shock

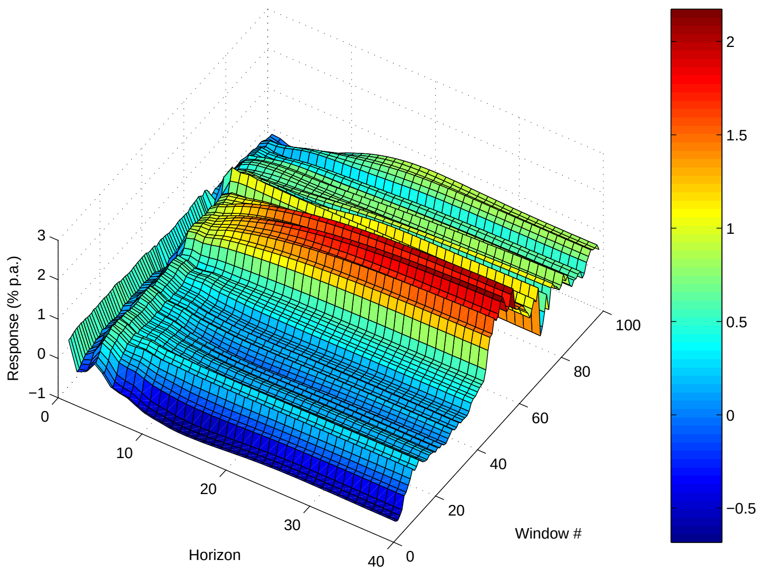


(c) Cross-sectional profiles of inflation shock

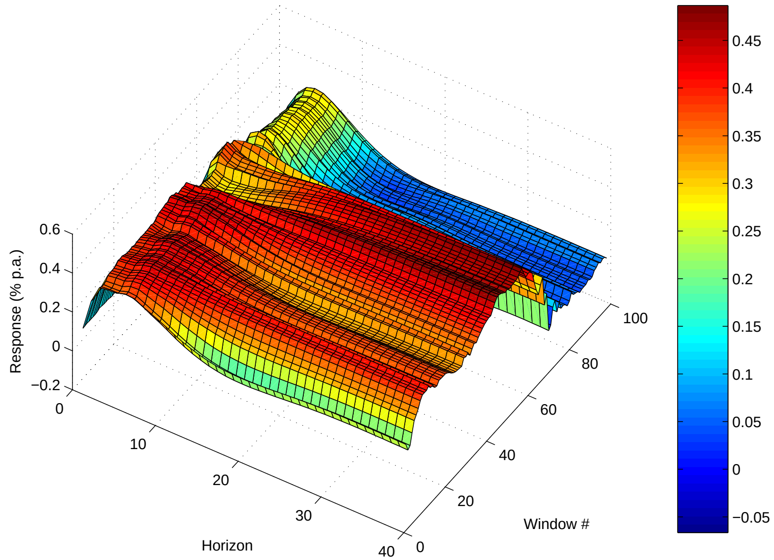


(d) Cross-sectional profiles of output gap shock

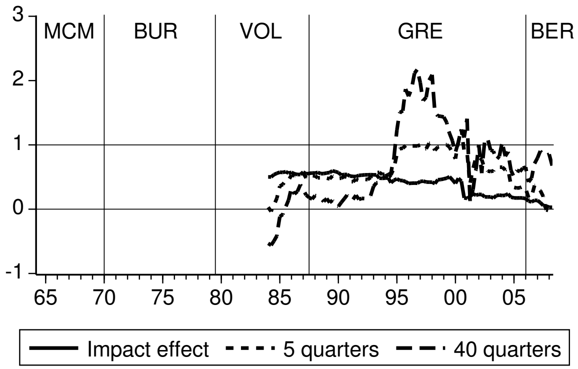
Figure 5: Rolling Dynamic Multipliers



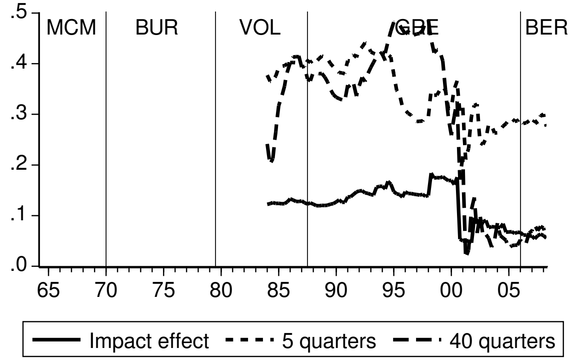
(a) OIRs of the nominal interest rate to a 1 s.d. positive inflation shock



(b) OIRs of the nominal interest rate to a 1 s.d. positive output gap shock

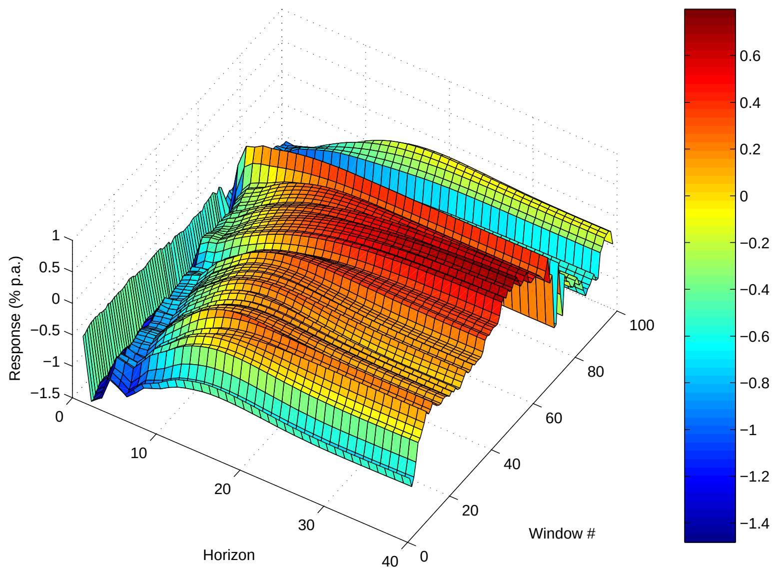


(c) Cross-sectional profiles of inflation shock

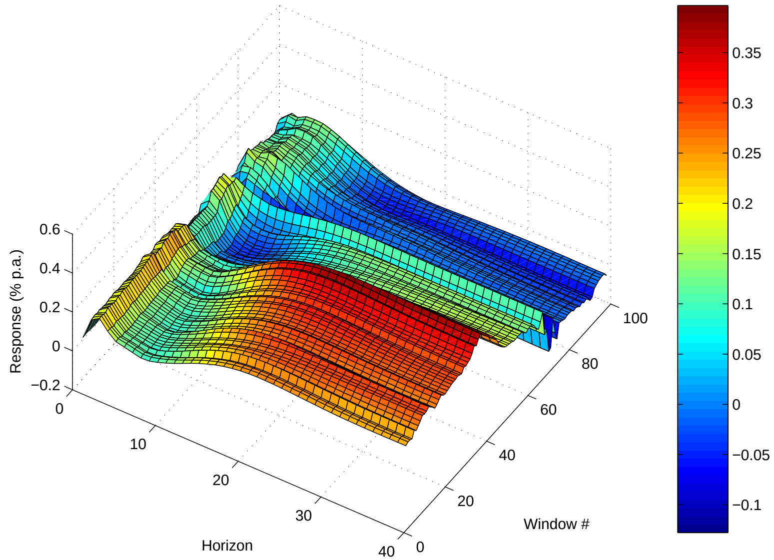


(d) Cross-sectional profiles of output gap shock

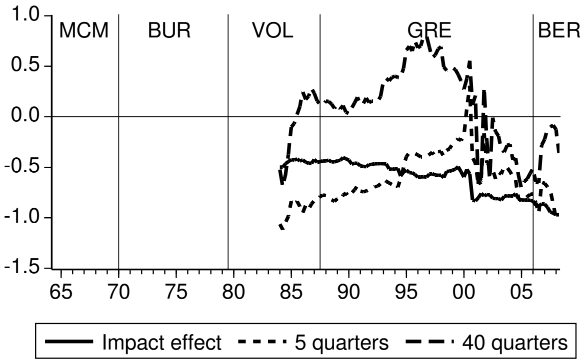
Figure 6: Rolling Orthogonalised Impulse Response Functions (Nominal Interest Rate, ARDL Long-Run Coefficients)



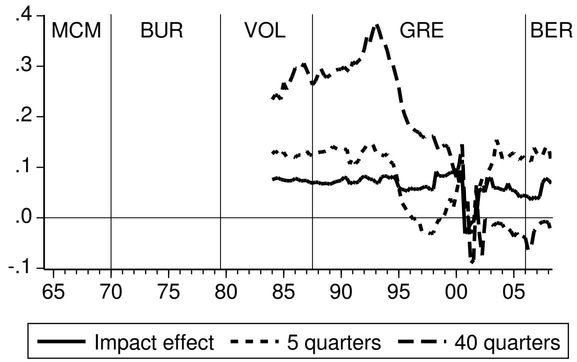
(a) OIRs of the real interest rate to a 1 s.d. positive inflation shock



(b) OIRs of the real interest rate to a 1 s.d. positive output gap shock

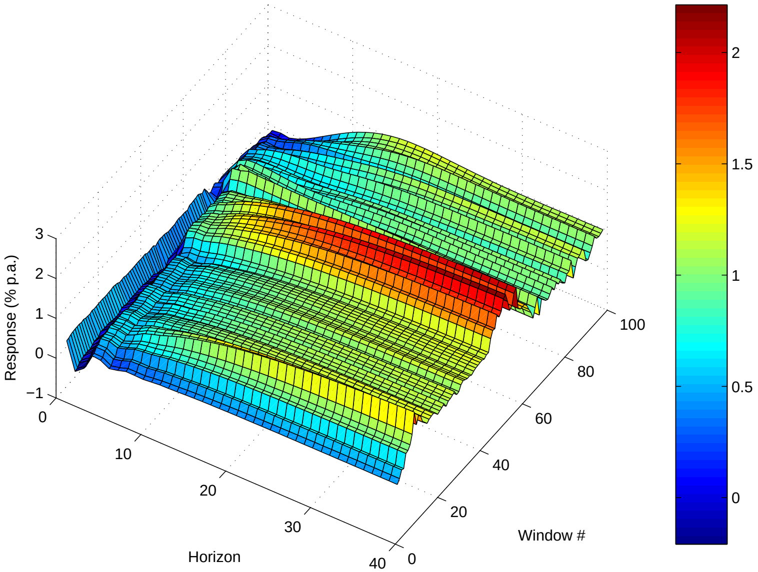


(c) Cross-sectional profiles of inflation shock

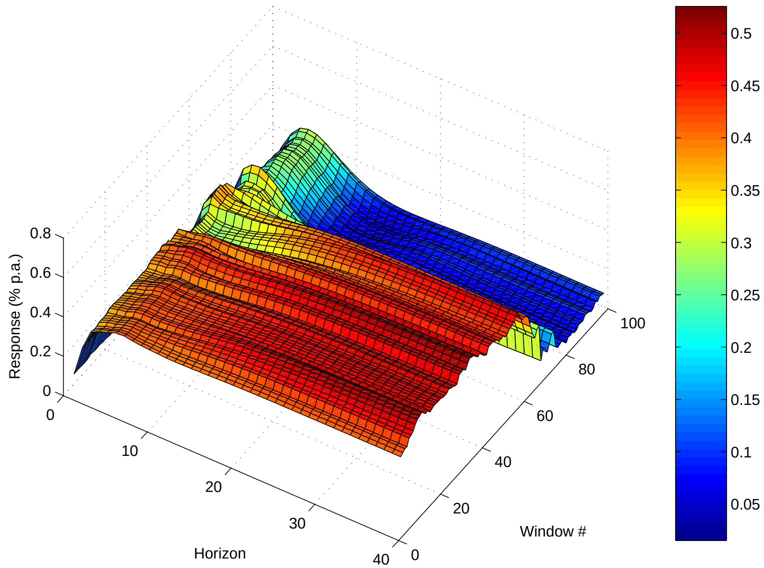


(d) Cross-sectional profiles of output gap shock

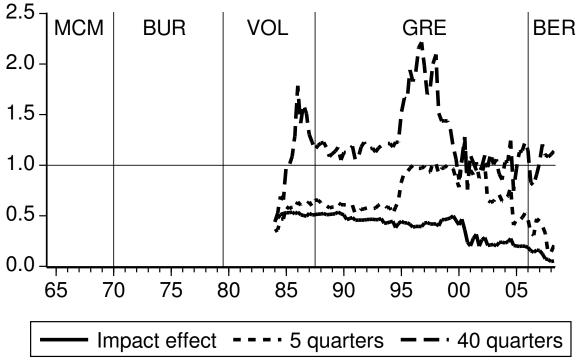
Figure 7: Rolling Orthogonalised Impulse Response Functions (Real Interest Rate, ARDL Long-Run Coefficients)



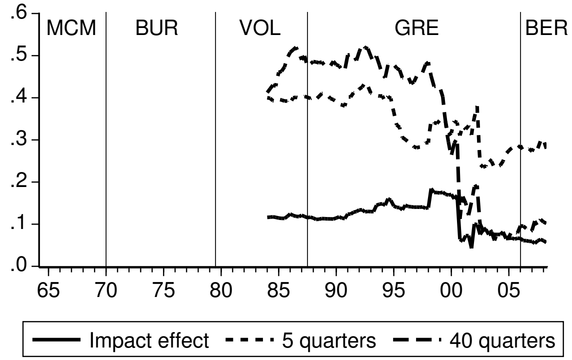
(a) OIRs of the nominal interest rate to a 1 s.d. positive inflation shock



(b) OIRs of the nominal interest rate to a 1 s.d. positive output gap shock

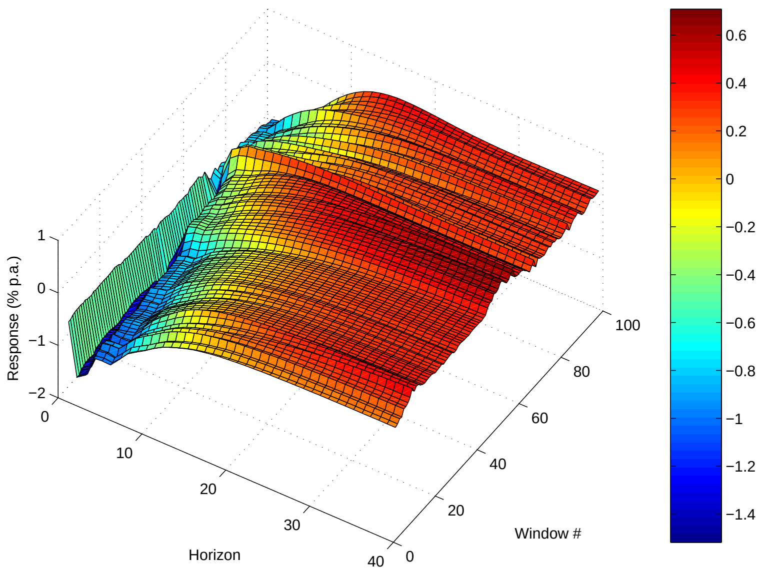


(c) Cross-sectional profiles of inflation shock

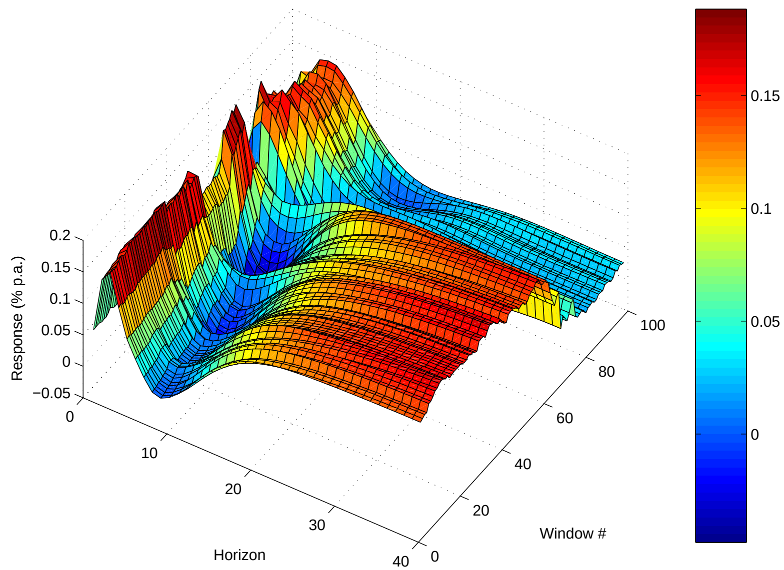


(d) Cross-sectional profiles of output gap shock

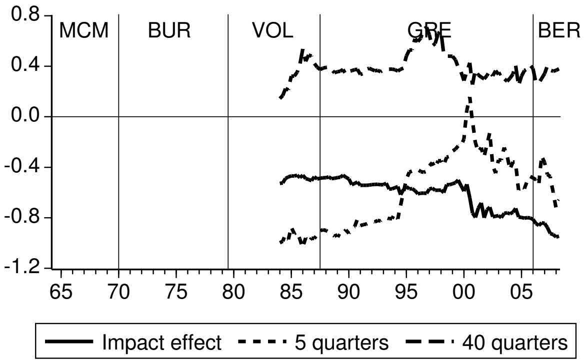
Figure 8: Rolling Orthogonalised Impulse Response Functions (Nominal Interest Rate, Taylor Coefficients)



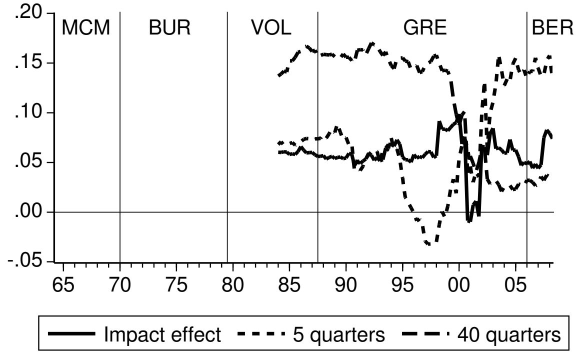
(a) OIRs of the real interest rate to a 1 s.d. positive inflation shock



(b) OIRs of the real interest rate to a 1 s.d. positive output gap shock



(c) Cross-sectional profiles of inflation shock



(d) Cross-sectional profiles of output gap shock

Figure 9: Rolling Orthogonalised Impulse Response Functions (Real Interest Rate, Taylor Coefficients)

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